Upgrades of the CMS Detector

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High Tech with a Human Touch™

About Me

- Postdoc at Florida Institute of Technology since 2015
- Ph.D. from University of Kansas (2014)
- Member of CMS collaboration since 2009
  - Physics analysis focused measurements of top quark production at the LHC
- Leading roles in detector upgrade program for Hadronic Calorimeter and the High Granularity Calorimeter for the HL-LHC
  - Received CMS Detector Award 2018 for leading the Forward Calorimeter Upgrades
- Active member of the LHC Physics Center at Fermilab
  - LPC Distinguished Research Award in 2019 & 2020

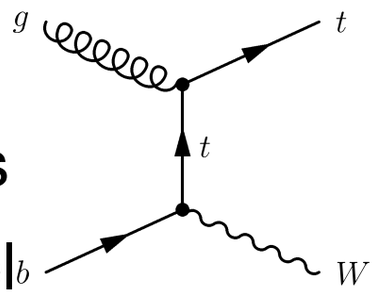
Physics Analysis

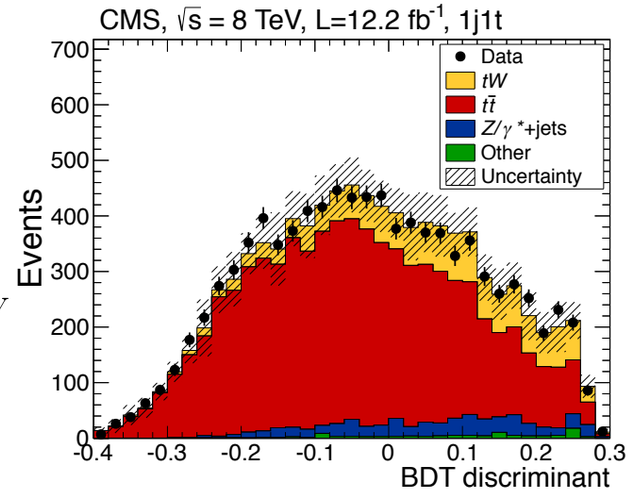
Measurement of top quark production

- Single top quark production in tW channel
  - Using machine learning to measure process
  - First observation for this production channel

Phys. Rev. Lett. 110 (2013) 022003

Phys. Rev. Lett. 112 (2014) 231802

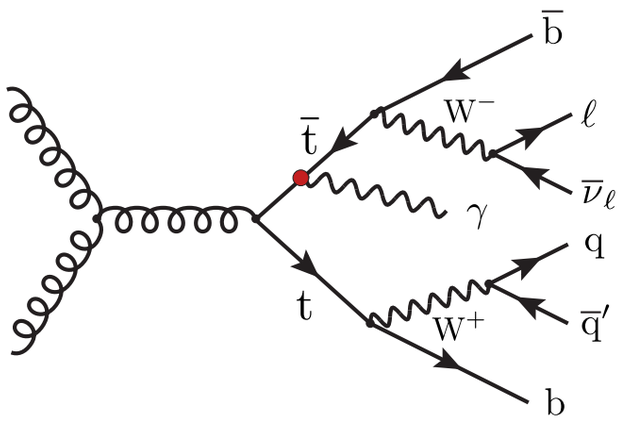


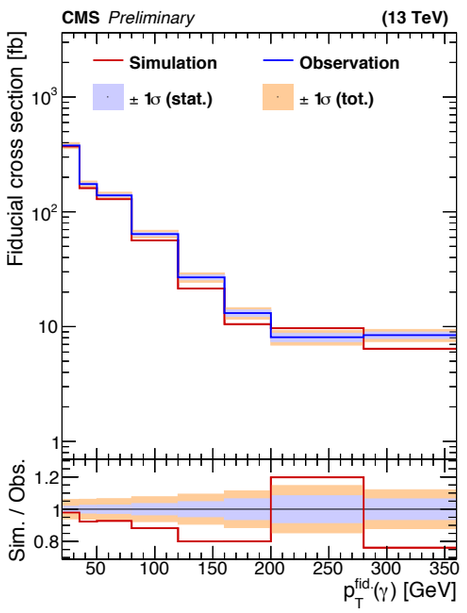


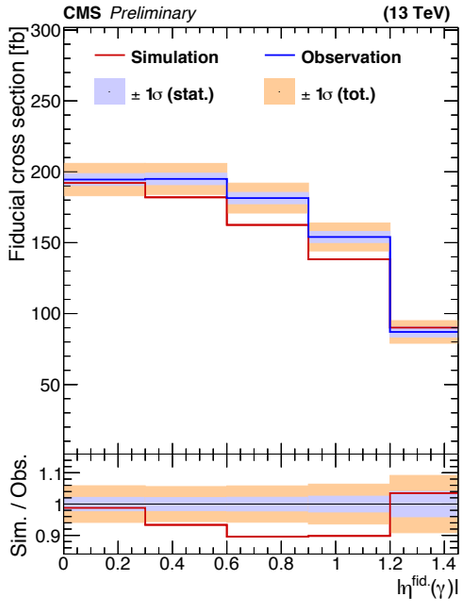
- Top quark pair production with a photon
  - Precision measurement of inclusive and differential cross section
  - Test of SM predictions, sensitive to EFT modification of top couplings

JHEP 10 (2017) 006

PAS-TOP-18-010



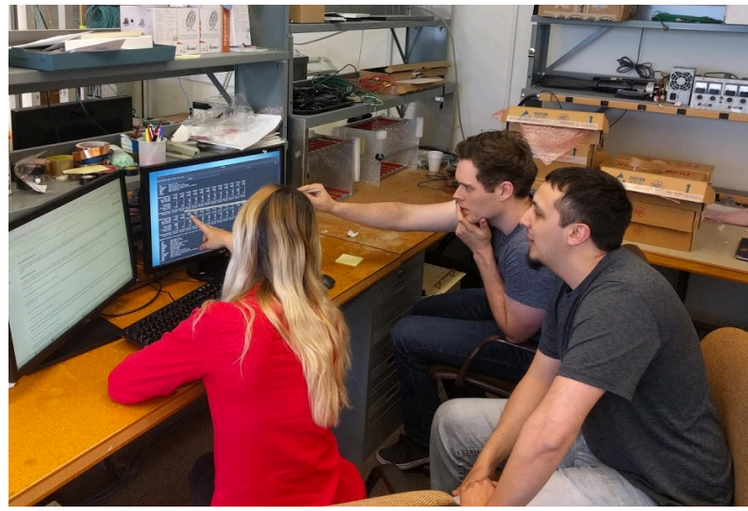




LHC Physics Center

- I have been an active member of the LPC since 2015
  - LPC Distinguished Researcher Award in 2019 and 2020
  - Contributing to many physics analysis and detector upgrade projects within the CMS community at Fermilab
- Facilitator for multiple schools and tutorials at the LPC
  - CMS Data Analysis School:
    - Lead tutorials in statistics and machine learning
    - Lead data analysis exercises in measurement of top quark mass and tt+γ cross section
  - Hands-on Advanced Tutorial Session (HATS):
    - Lead tutorials on CMS Detector Upgrades, data analysis in Python, and machine learning
- Local organizer for workshop on Top Quark Physics at the Precision Frontier (January 2018 and May 2019)

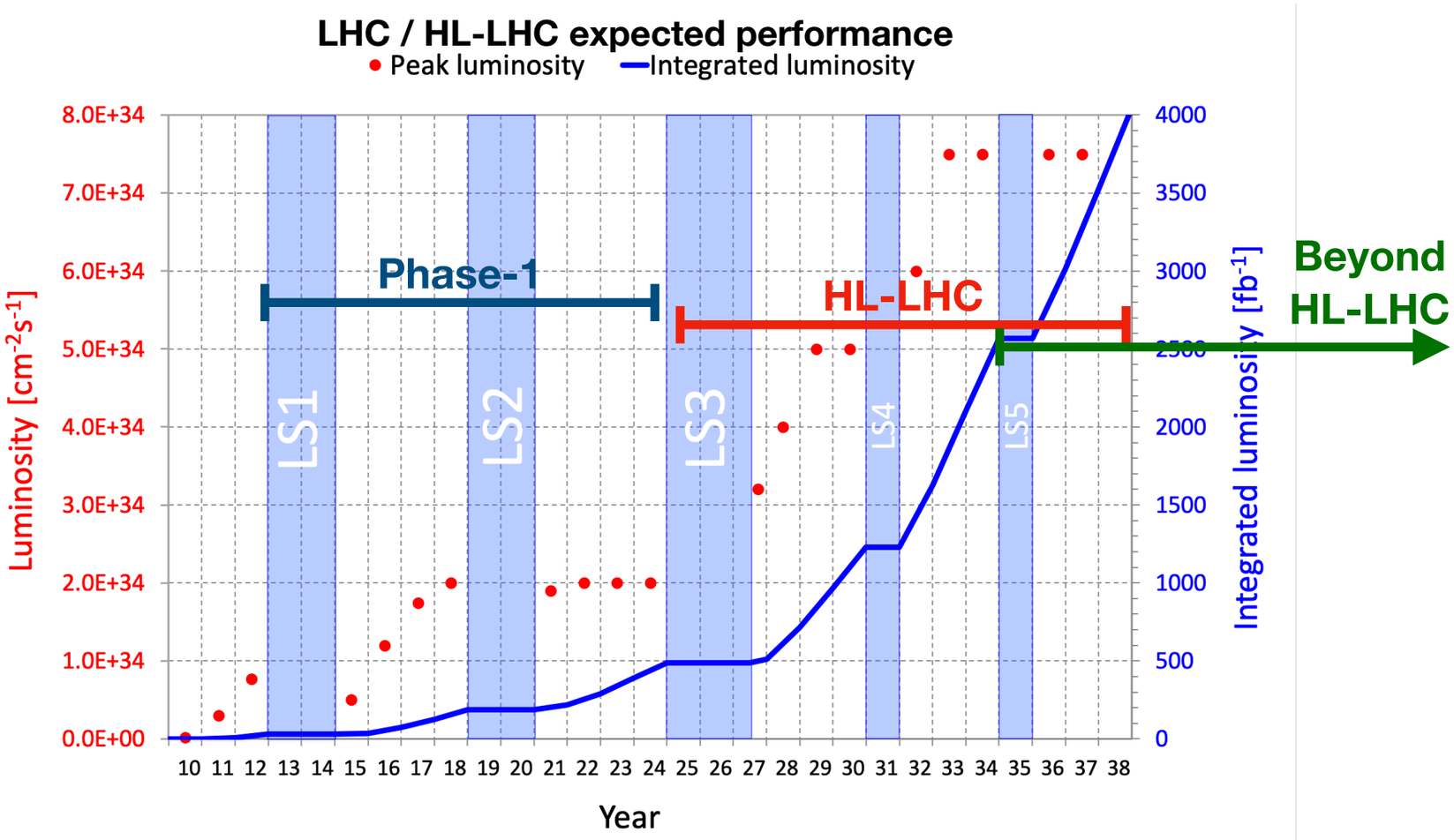
Students at the CMS Detector Upgrades HATS



2019 Top Quark Physics at the Precision Frontier

Detector Upgrades

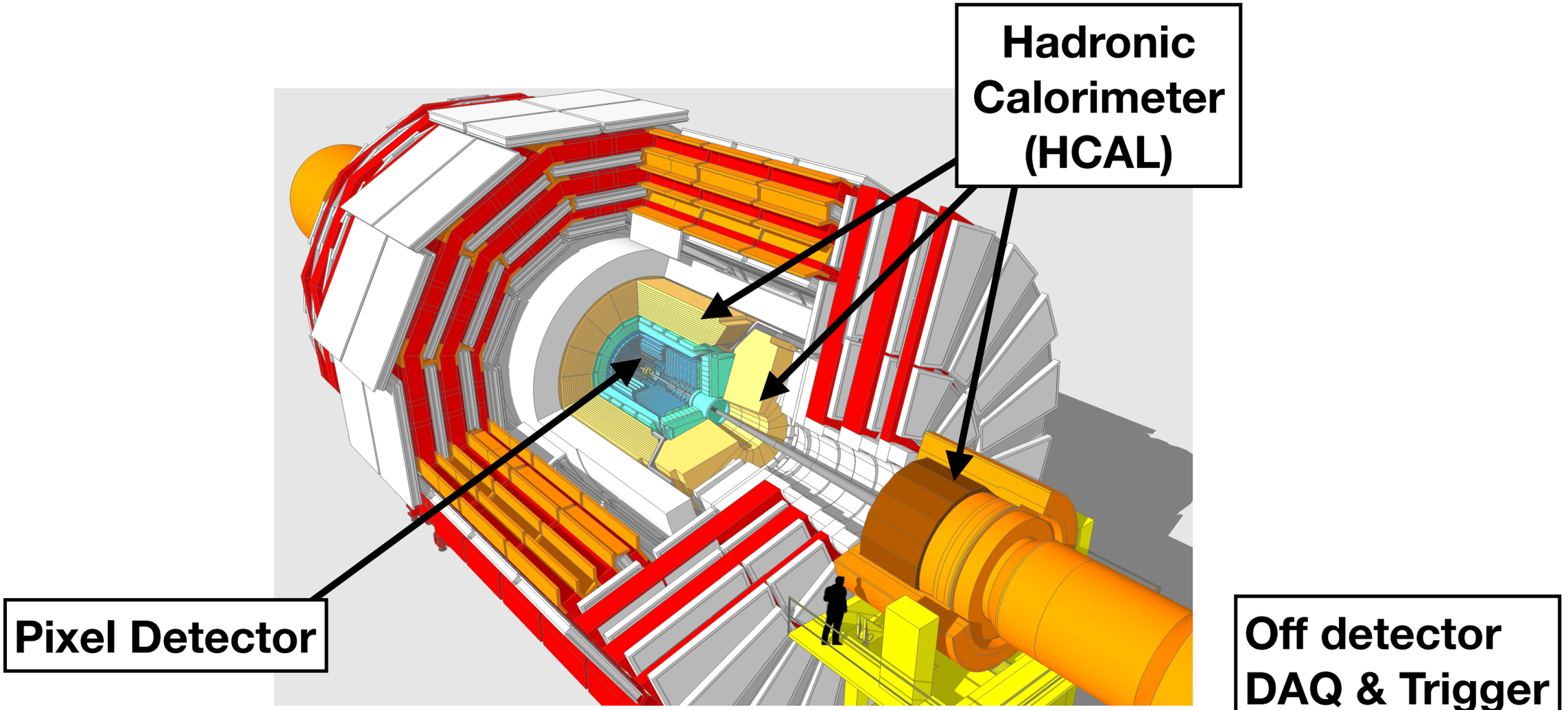
- Upgrades to detectors are required in order to cope with the higher rates and accumulated radiation damage, while maintaining a consistent or improving level of precision
- Three main regimes
  - **Phase-1** : Improvements to maintain performance through the end of Run 3
  - **HL-LHC** : Higher precision while coping with the higher data rates and radiation levels
  - **Beyond the HL-LHC** : More extreme environments while extending precision/sensitivity



Phase-1 Upgrades

CMS Detector Upgrades

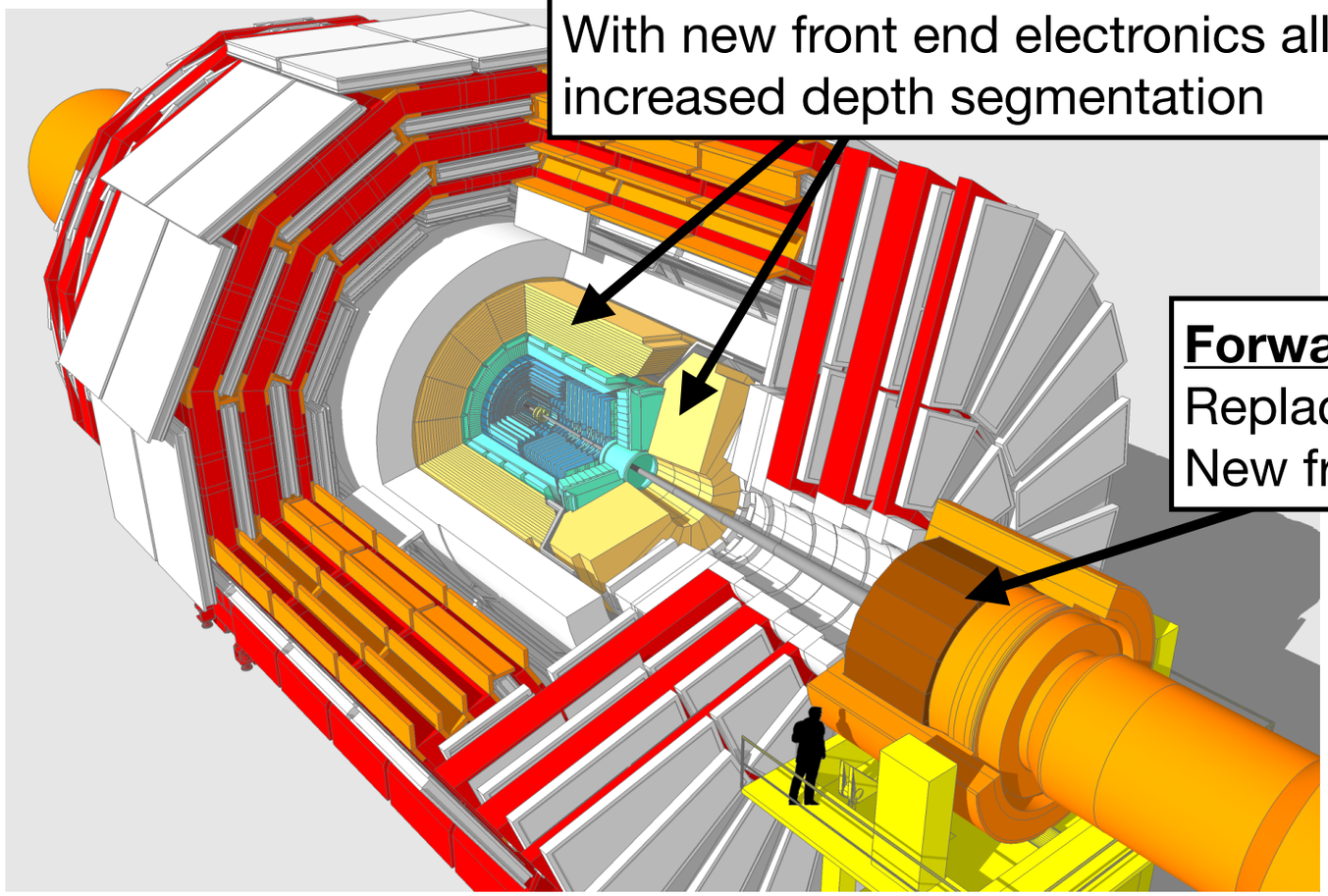
Phase-1 Upgrades



HCAL Upgrades

Phase-1 Upgrades Overview

Endcap (HE) : 2018
<u>Barrel (HB): 2019-2020</u>
First use of SiPMs in collider detector
With new front end electronics allows increased depth segmentation

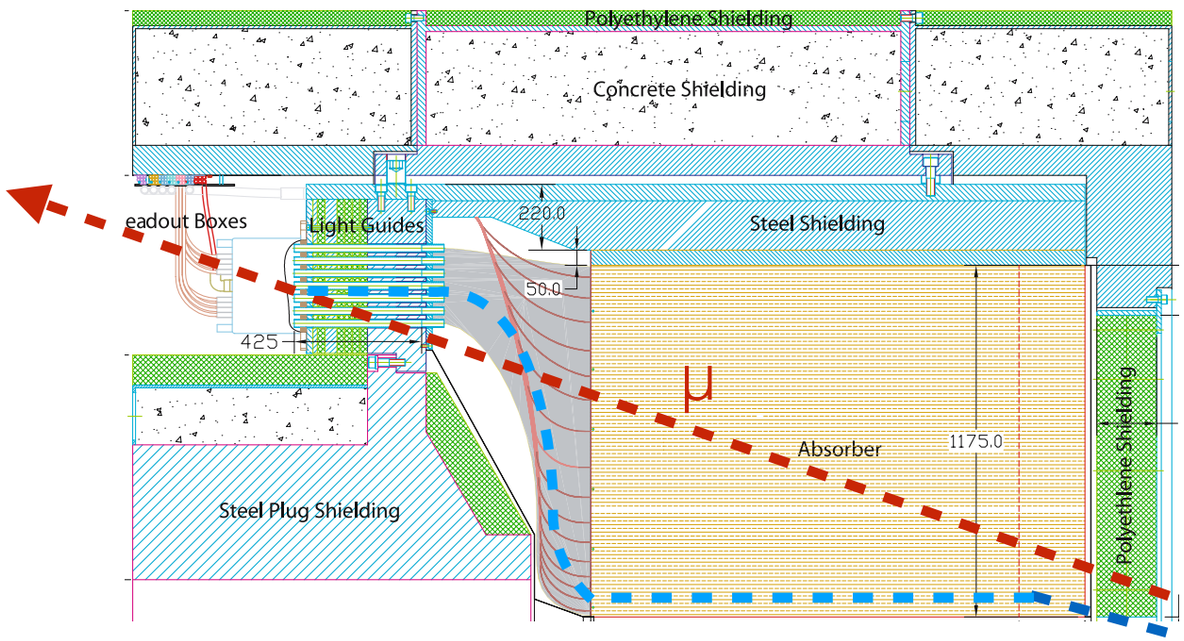


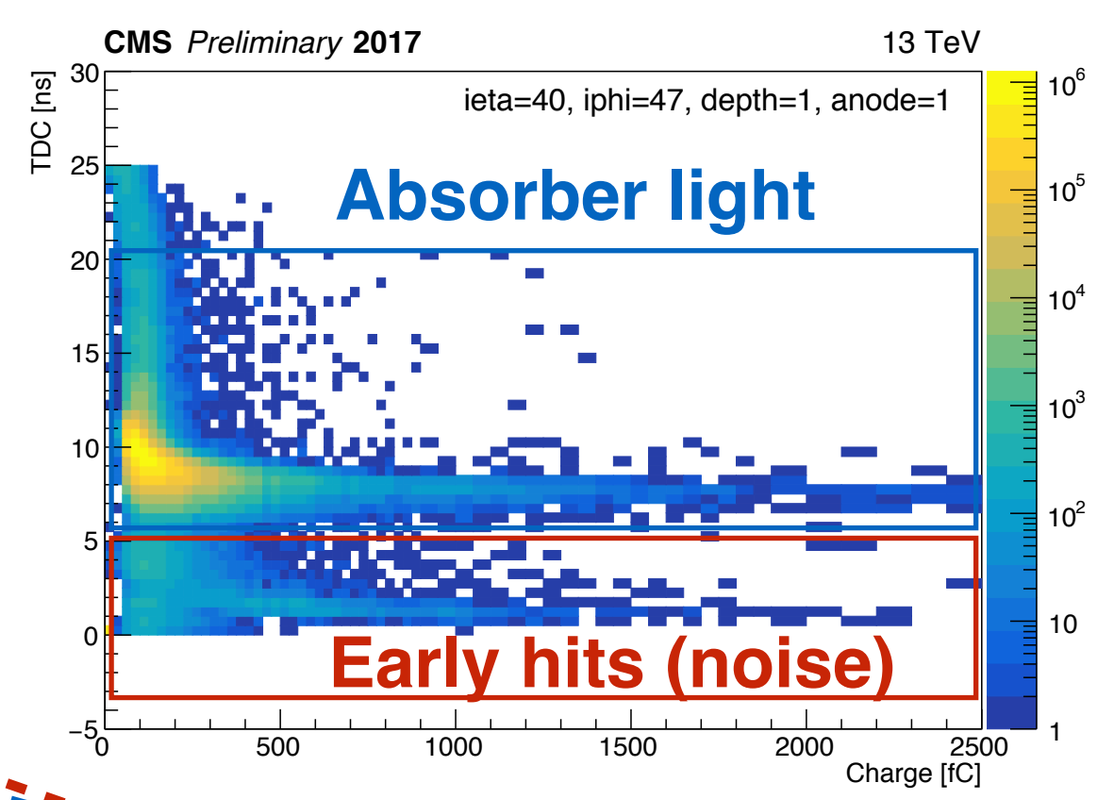
<u>Forward (HF): 2017</u>
Replacement of PMTs
New front end electronics

HCAL Upgrades

Forward Hadronic Calorimeter (HF)

- Significant background noise from anomalous hits after the absorber
  - Punch through particles interacting with fiber bundles or PMTs
- Mitigated by inclusion of pulse timing information in upgraded readout
  - Capable of discriminating early-arriving punch through signals from in-time light from the absorber



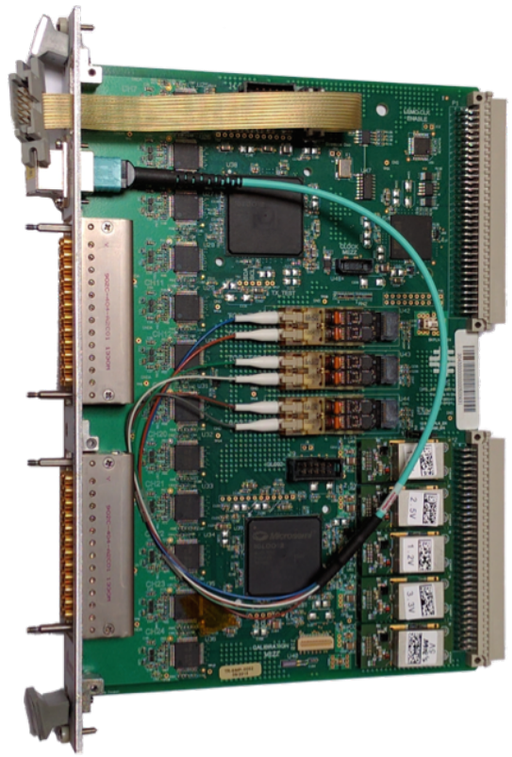


HCAL Upgrades

HF Electronics Testing & Integration

- New front end electronics based on the Fermilab designed **QIE10 ASIC** (charge integrator and encoder)
- I led a team of approx. 20 students, postdocs, and engineers in the testing, burn in, and installation of upgraded detector
  - Full tests of functionality
  - Integration into existing readout system
  - Calibration of readouts
  - Installation onto the detector
  - Commissioning with collision data
- Large effort, resulting in successful upgrade of the detector during winter of 2016/17
- I received CMS Detector Award for my leadership role in this project

QIE 10 Card for HF readout

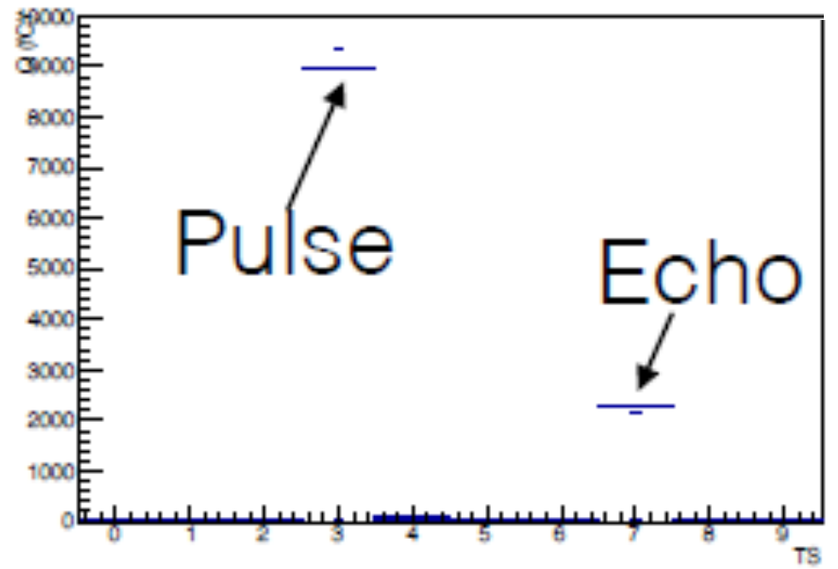


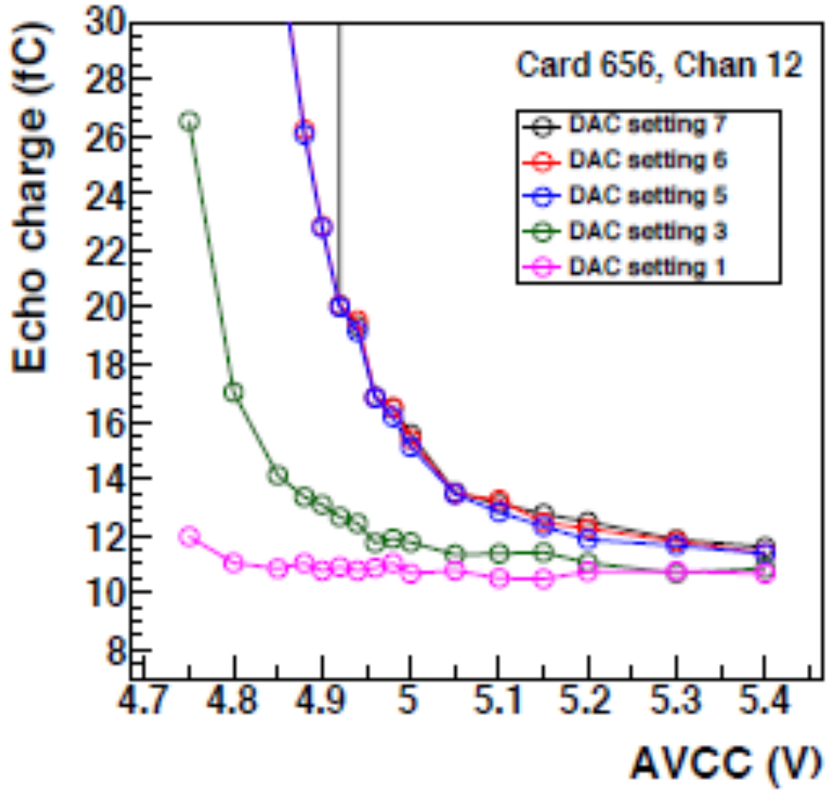
HF Electronics Burn-In At CERN

HCAL Upgrades

Challenges in HF Testing / Commissioning

- Throughout the testing and commissioning process, issues were identified and remedied
  - Quality issues in initial assembly
  - Fragility of cabling
  - ★ Mismatch of supplied voltages to QIE ASIC
- Problem identified through an “echo” 4 clock cycles after large signal pulses
  - QIE internally cycles through 4 capacitors (charging, reading out, discharging)
- Working with FNAL engineers who designed the ASIC and boards (Tom Zimmerman and Terri Shaw), we were able to identify the issue
  - Voltage supplied by DC/DC converter too low to allow full discharge of circuit
- Able to fix the problem with a modification to the DC/DC converters, increasing nominal voltage to 5.2 V
  - Same solution was able to be applied to prevent issue in barrel and endcap electronics



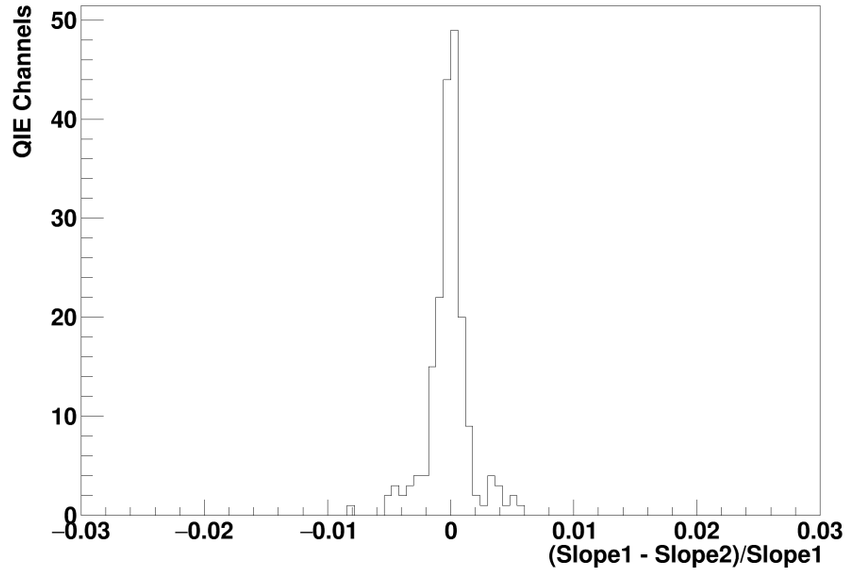


HCAL Upgrades

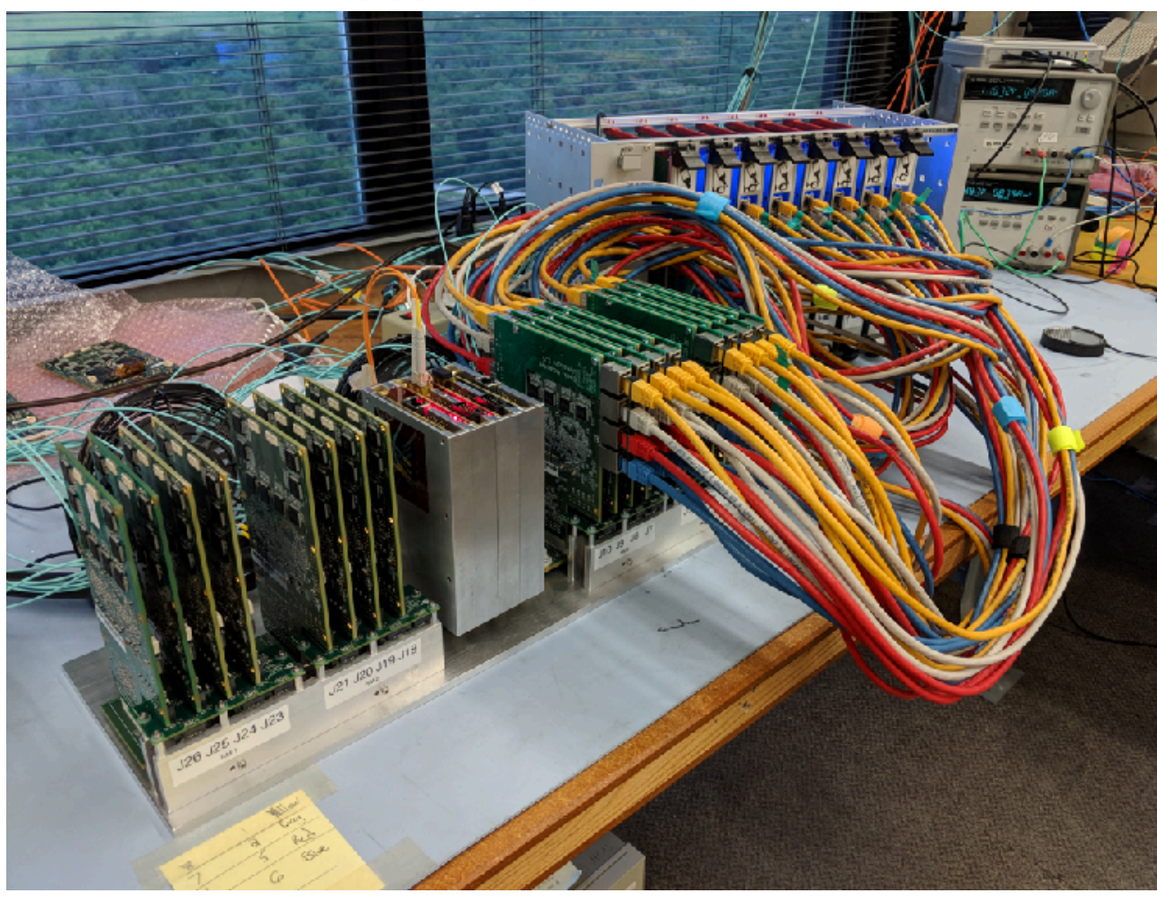
QIE Calibrations

- QIE's are responsible for digitizing the analog electrical signals produced by the photodetectors
  - Accurate measurement of charge essential for reconstruction of energy depositions in the detector
- Led the development and execution of the calibration for all HCAL upgrades
- Calibration systems developed for each subsystem
  - Lessons learned in each subdetector carried over to the design and procedures of the next
- Each channel calibrated individually
  - HF : 200 boards x 24 QIE/board
  - HE/HB : ~1000 boards x 12 or 16 QIE/board
- Calibration measured to 0.3% precision
  - Measured response of all channels fed back into CMS event reconstruction algorithms

Precision of QIE calibration over independent measurements



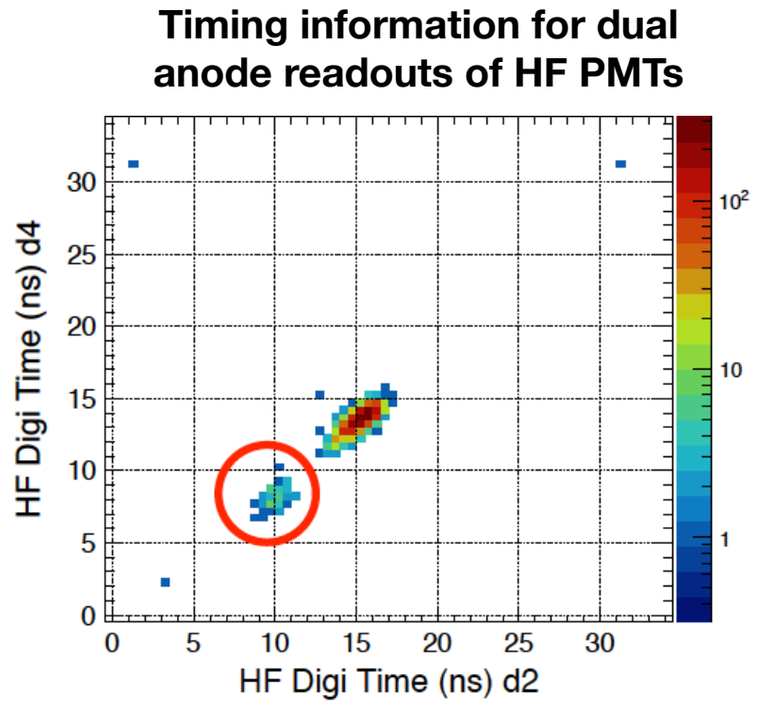
Calibration setup for barrel readout electronics in Wilson Hall



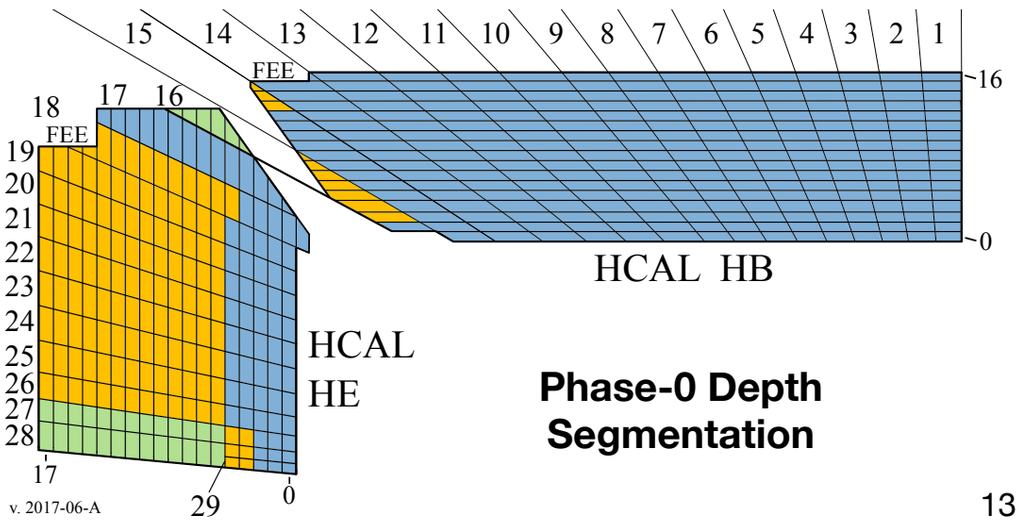
HCAL Upgrades

Summary

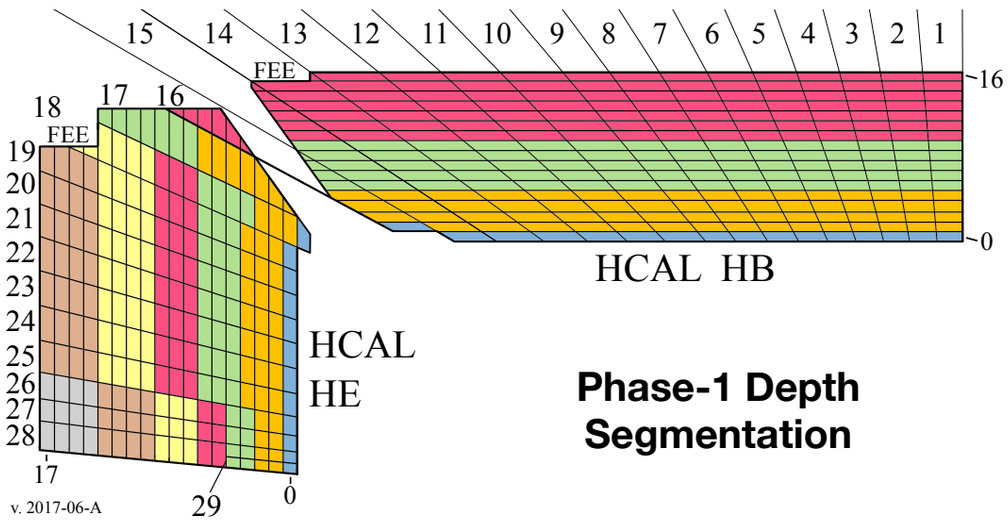
- Phase-1 Upgrades of hadronic calorimeter have been very successful
  - Upgrades of the **HF subdetector** have provided significant improvements in the ability to identify and reject anomalous hits in the detector
  - Upgrades of **barrel and endcap calorimeters** improved detector response and added increased segmentation



HCAL Depth Segmentation before and after upgrades



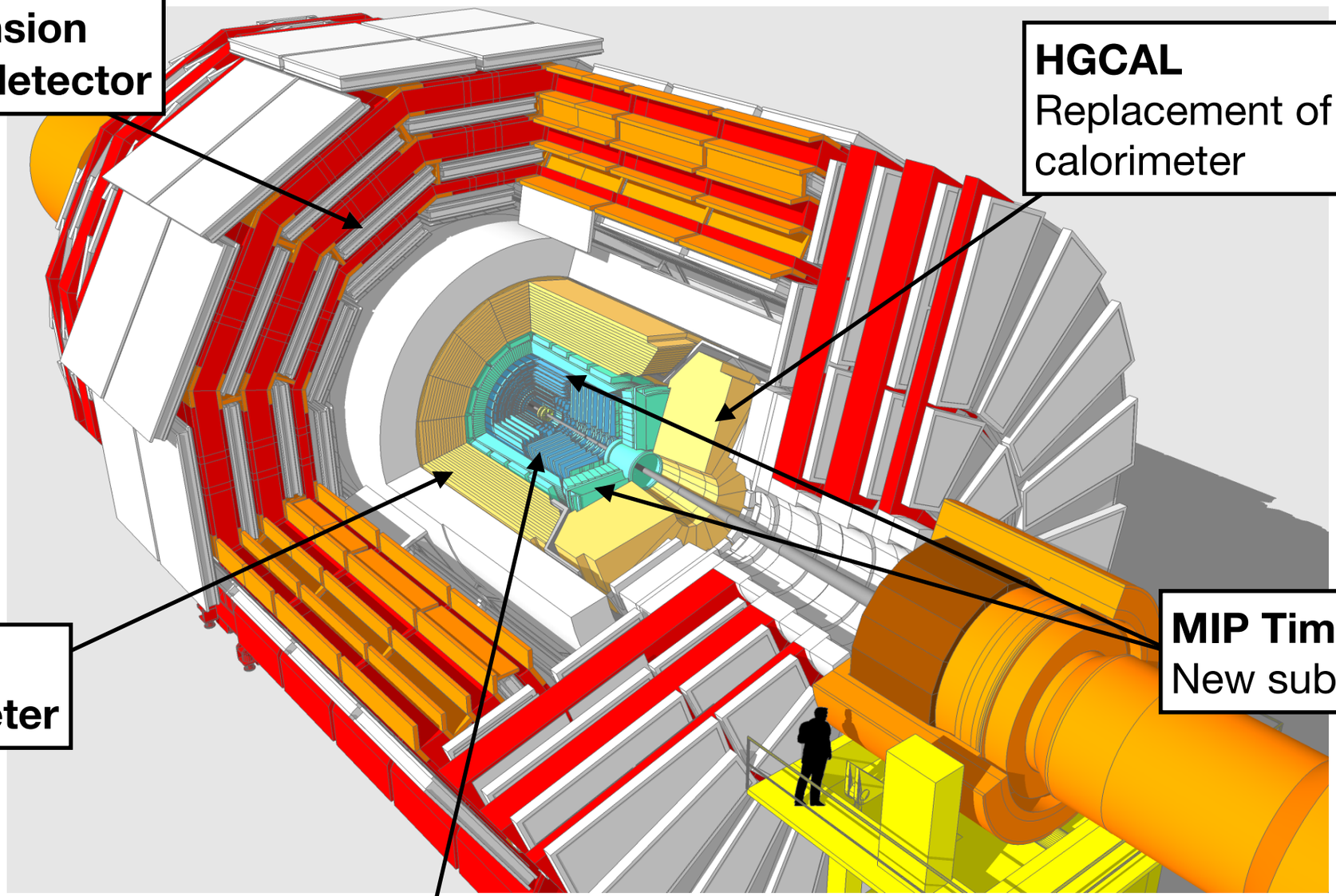
Phase-0 Depth Segmentation



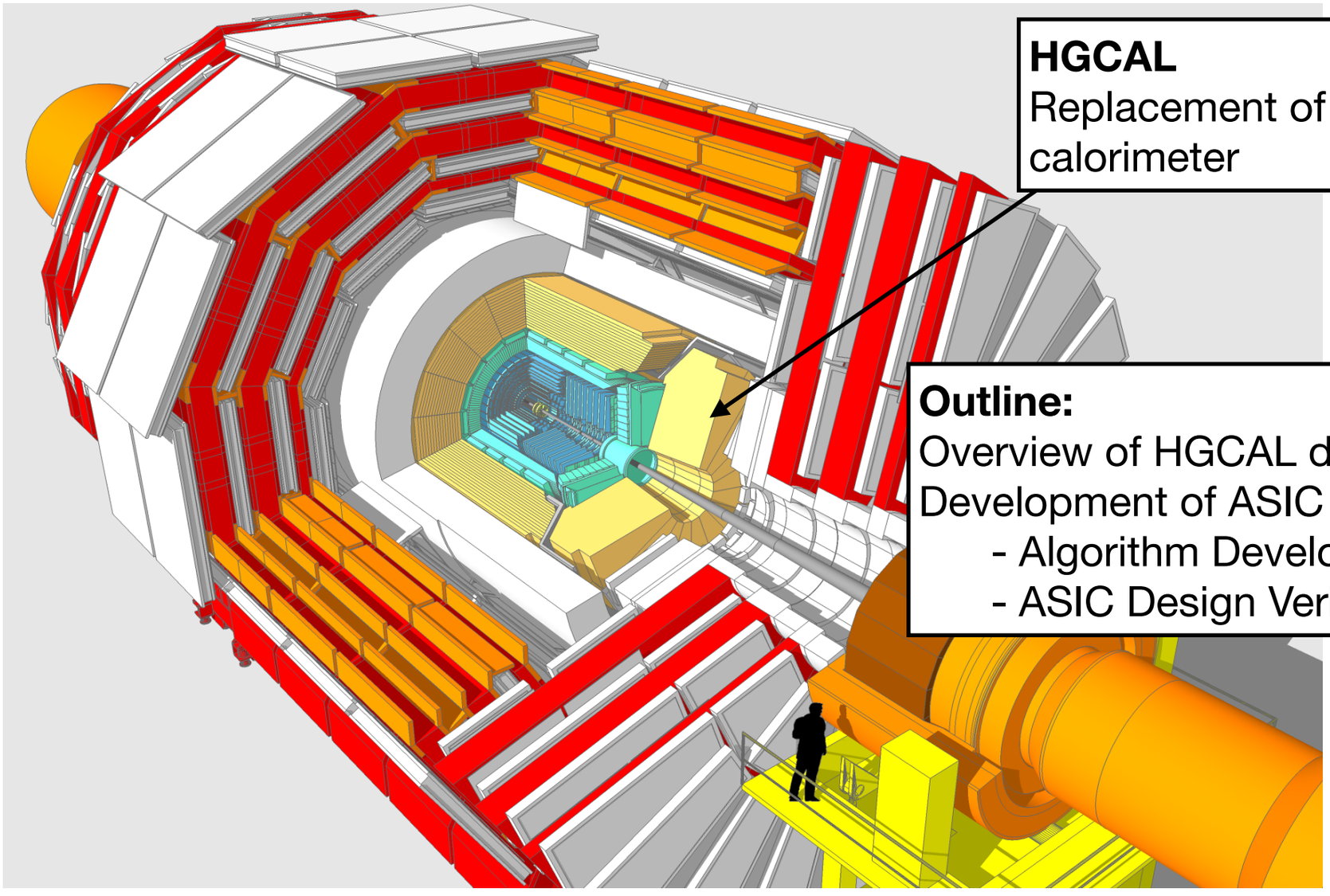
Phase-1 Depth Segmentation

HL-LHC Upgrades

High Luminosity LHC Upgrades



High Luminosity LHC Upgrades

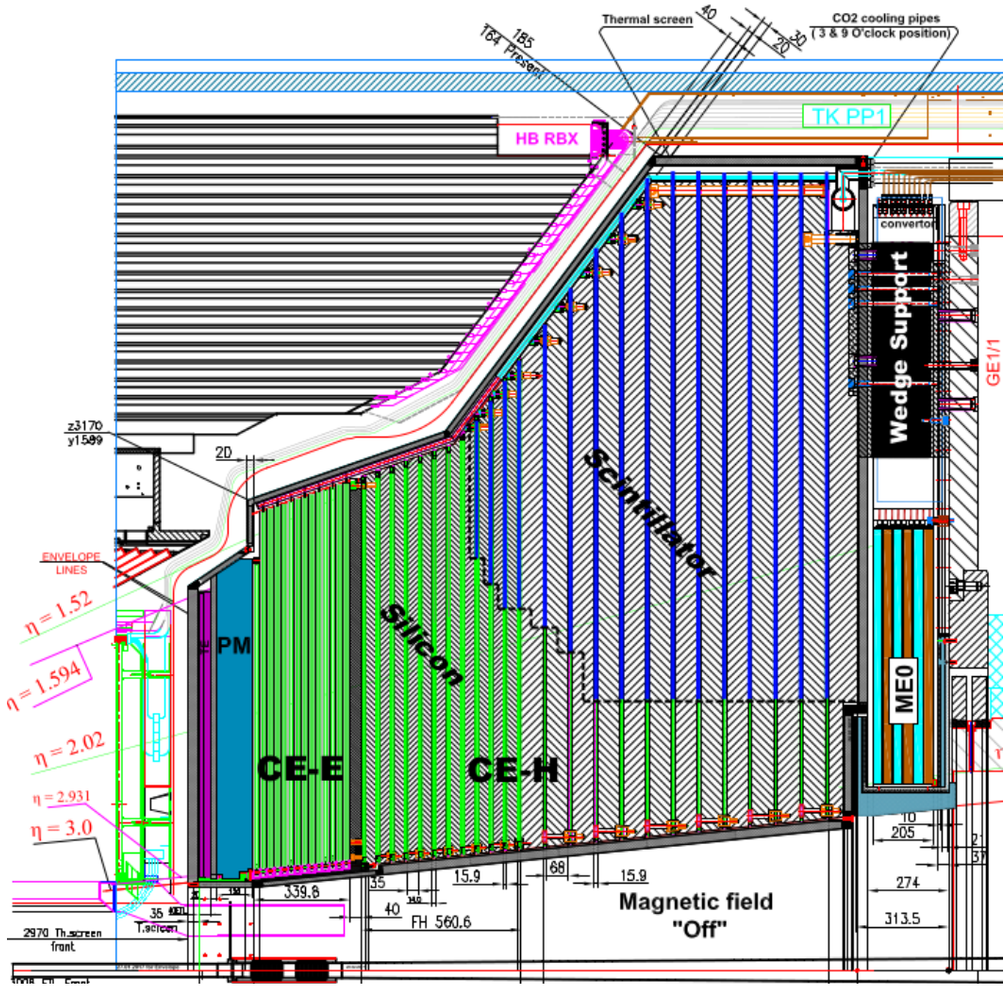


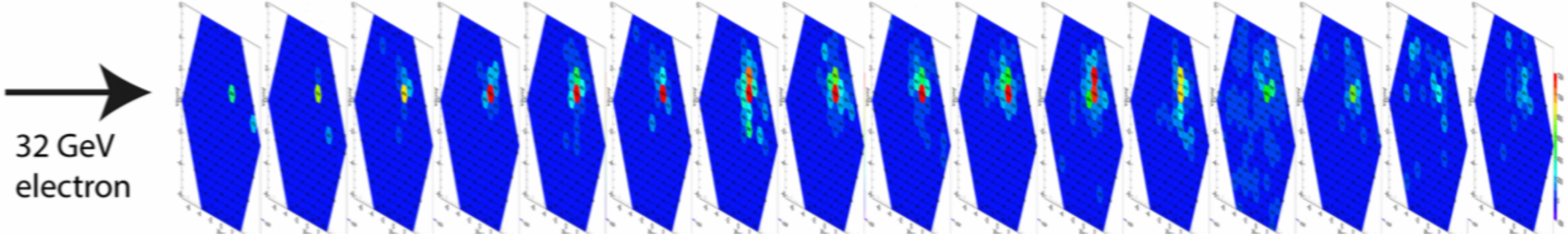
HGCAL
Replacement of endcap calorimeter

Outline:
Overview of HGCAL detector
Development of ASIC for readout
- Algorithm Development
- ASIC Design Verification

High Granularity Calorimeter

- Complete replacement of current end-cap calorimeters to handle increased luminosity and radiation of HL-LHC
- 5-D imaging calorimeter
  - Provides precise position, energy, and timing information of shower development
- Comprised of mix of silicon and scintillator detectors
- Over 6 million total channels
  - Factor of 100 increase over existing detector

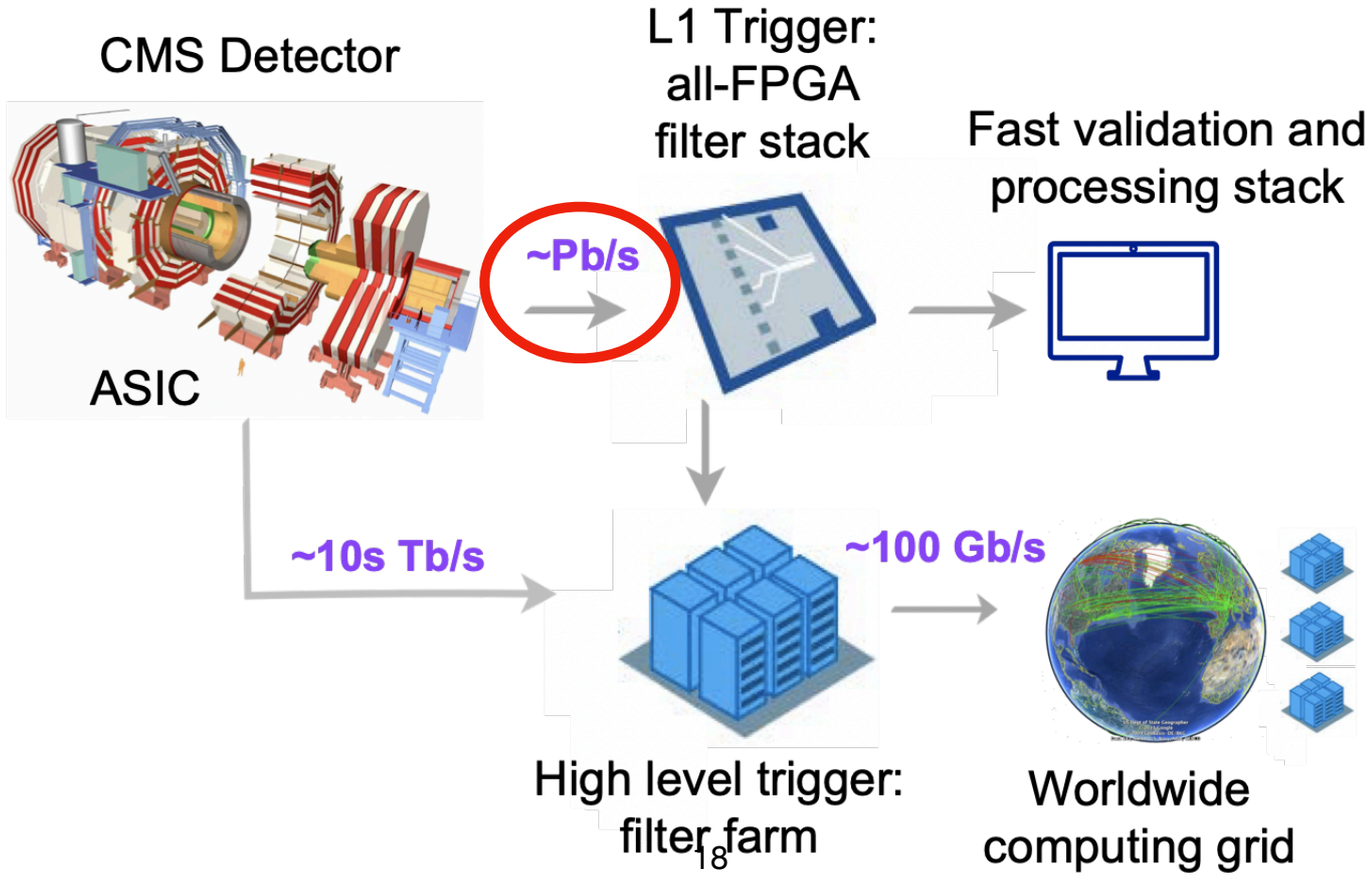




High Granularity Calorimeter

Endcap Concentrator (ECON) ASIC

- Data volumes from the large number of channels will present challenges in readout
  - Readout of trigger information at 40 MHz
- Endcap Concentrator ASIC (or ECON) being developed to handle data volumes from HGCAL
  - Apply one of a number of algorithms to reduce data volumes to a manageable level
  - Transmit data to backend where it can be combined with information from rest of detector to make a trigger decision

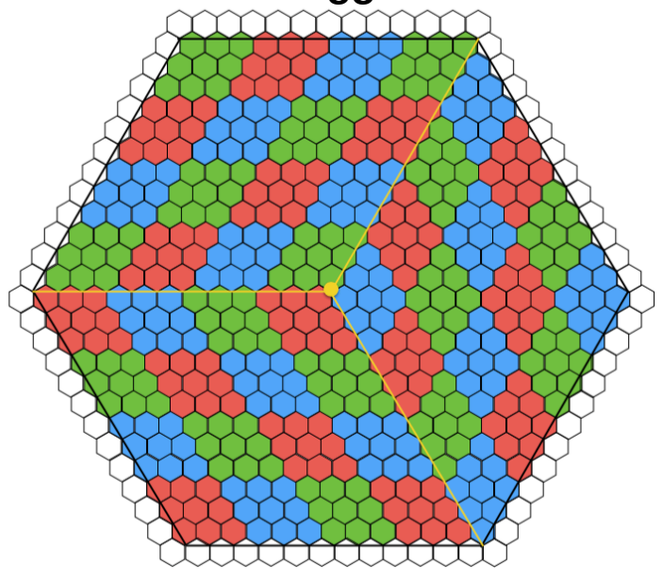


High Granularity Calorimeter

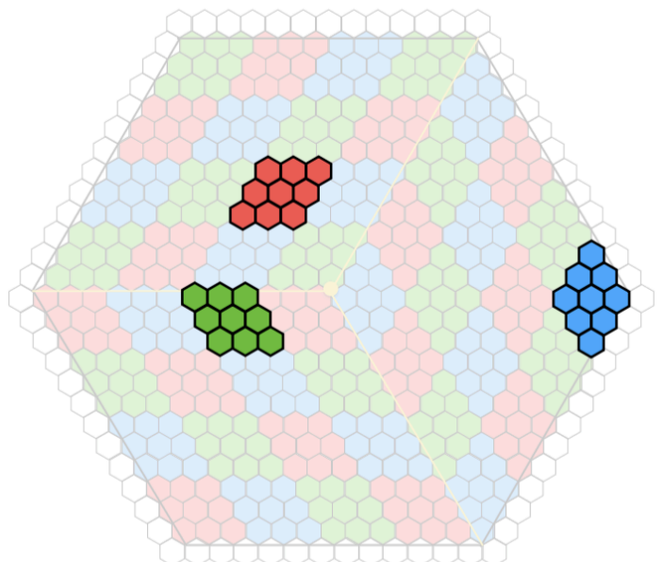
Algorithm Development

- For Level-1 trigger, channels are grouped into “trigger cells”
  - Trigger cell data is still too much to transmit at 40 MHz for trigger evaluation
- ECON will have multiple algorithms for further data reduction
  - Simplest: Threshold algorithm, reading out only cells above programmable threshold
  - Most novel: Autoencoder, implement machine learning algorithm
    - Reconfigurable neural network for data compression
    - First use of machine learning on radiation tolerant ASIC for HEP

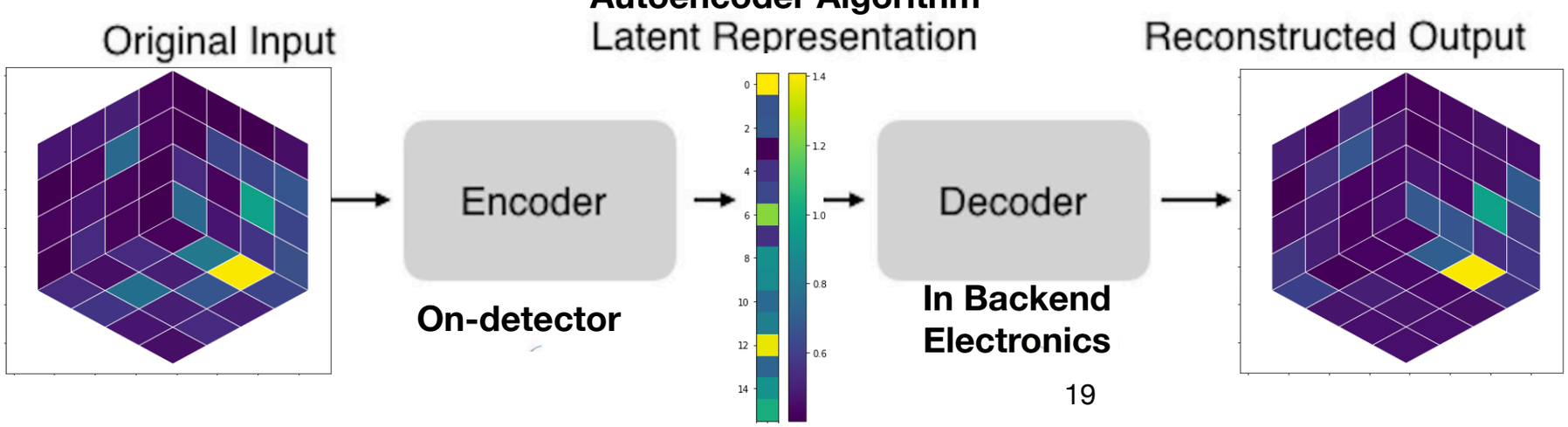
432 silicon sensor cells grouped into 48 trigger cells



Selection of trigger cells above threshold



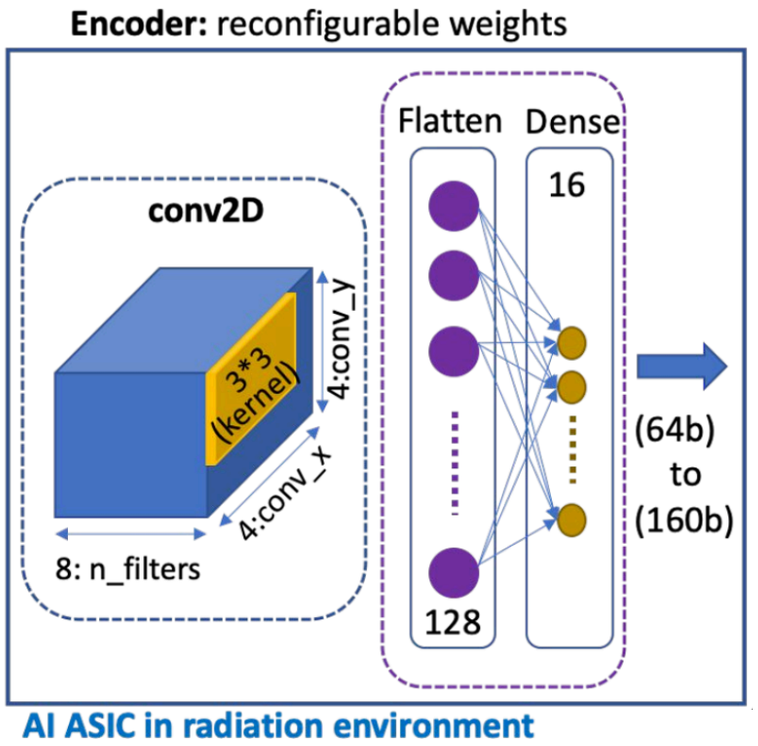
Autoencoder Algorithm

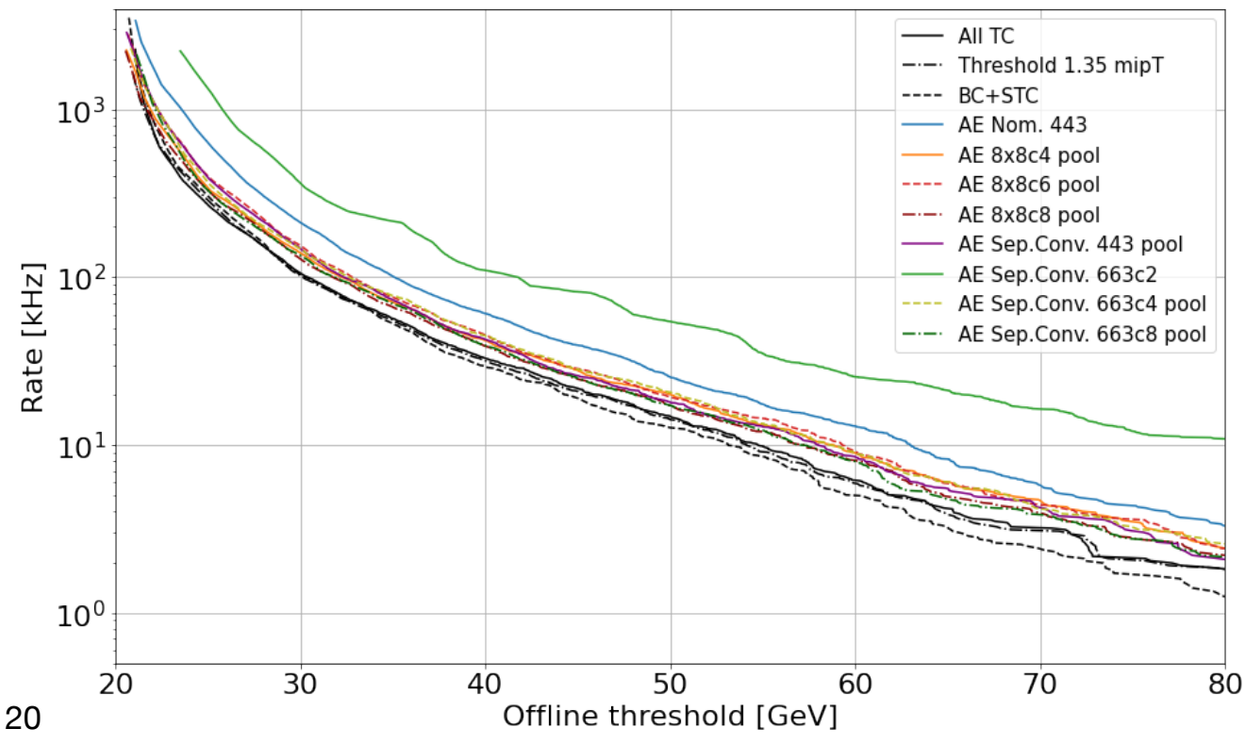


High Granularity Calorimeter

AutoEncoder Algorithm Optimization

- Weights of the AutoEncoder algorithm are reprogrammable, allowing retraining of network to suit future needs
  - General network architecture is fixed in the ASIC
- Work with engineers to understand the limitations, and find ways of optimizing the performance
  - ASIC Metrics: Power, Size, # of registers
  - Physics Metrics: Reconstruction eff., Trigger rates



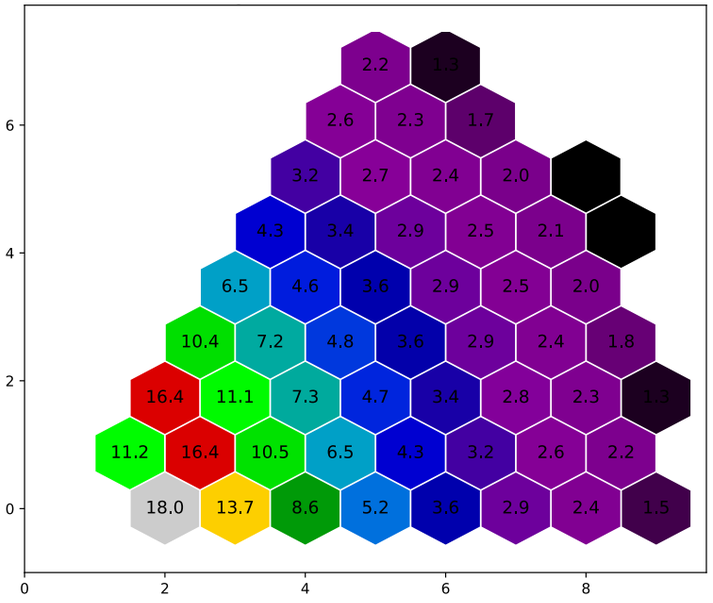


High Granularity Calorimeter

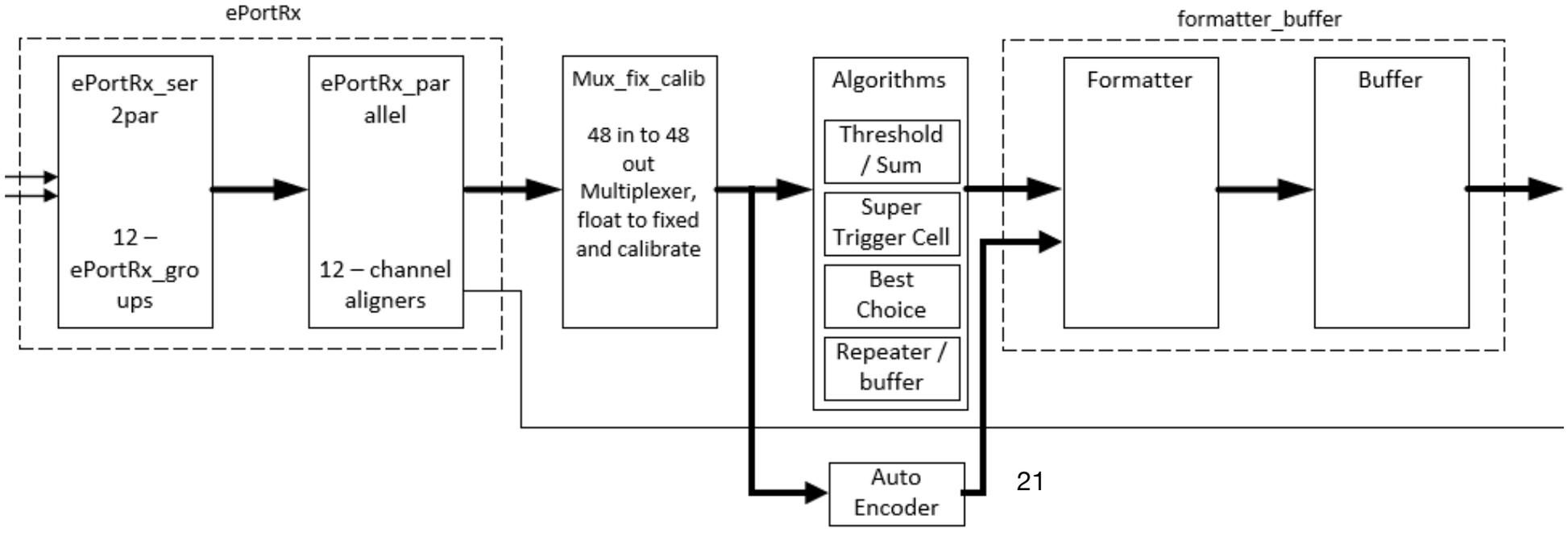
Bit-level emulation and verification

- Developed software based emulation of full functionality of the ECON
  - Provides bit-wise predictions of values at each block of the chip
  - Invaluable in understanding performance and operating conditions
  - Independent implementation from ASIC designers, has been critical in discovering and correcting bugs in design
- Working closely with the engineers Fermilab ASIC Design group
  - Intermediary between the design group and the physicists
  - Emulation has been crucial for development of coverage and design verification plans to ensure full performance of the design

Occupancy of ECON Buffer based on emulator simulation



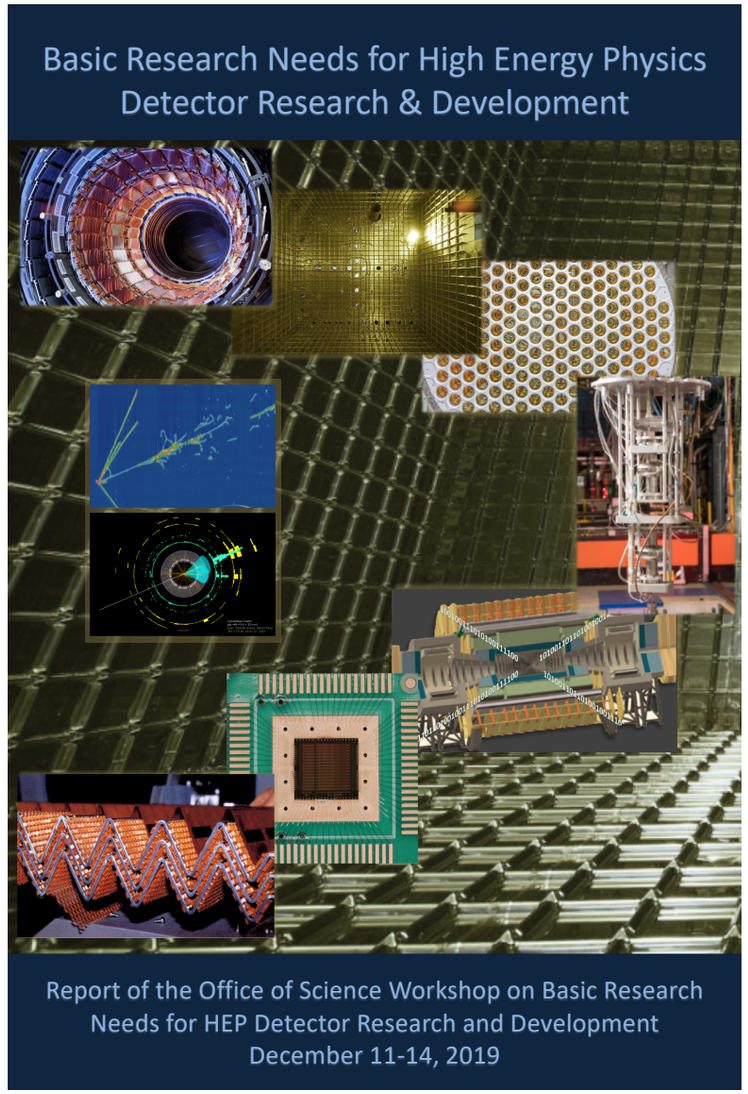
Block Diagram of ECON-T ASIC



Beyond the HL-LHC

Future Detector Development

- Beyond the HL-LHC, processes like Snowmass and European Strategy for Particle Physics are looking at what the future of the field will look like
- New experiments and accelerators are being envisioned
  - ILC or other ee colider,
  - FCC
  - Muon collider
- The primary challenges will look very familiar, just at higher levels
  - Coping with extreme environments and data rates
  - Improving measurement precision
- DOE Basic Research Needs Study highlights the types or new detector and instrumentation technologies that will be needed to achieve these goals of these experiments

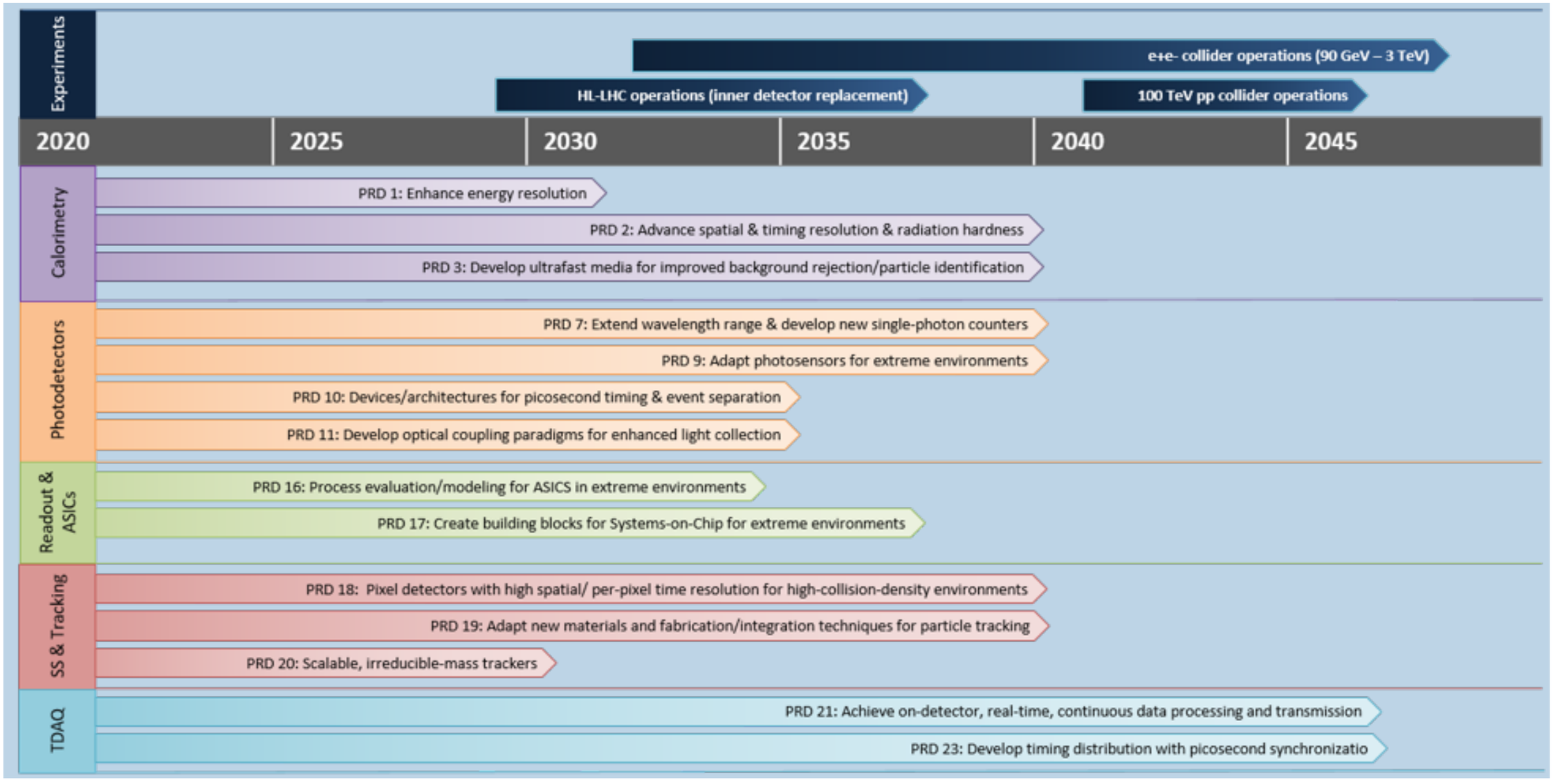


https://science.osti.gov/-/media/hep/pdf/Reports/2020/DOE_Basic_Research_Needs_Study_on_High_Energy_Physics.pdf

Future Detector Development

- To achieve high level of precision required for the physics goals of these experiments, improvements in detector technologies will be required

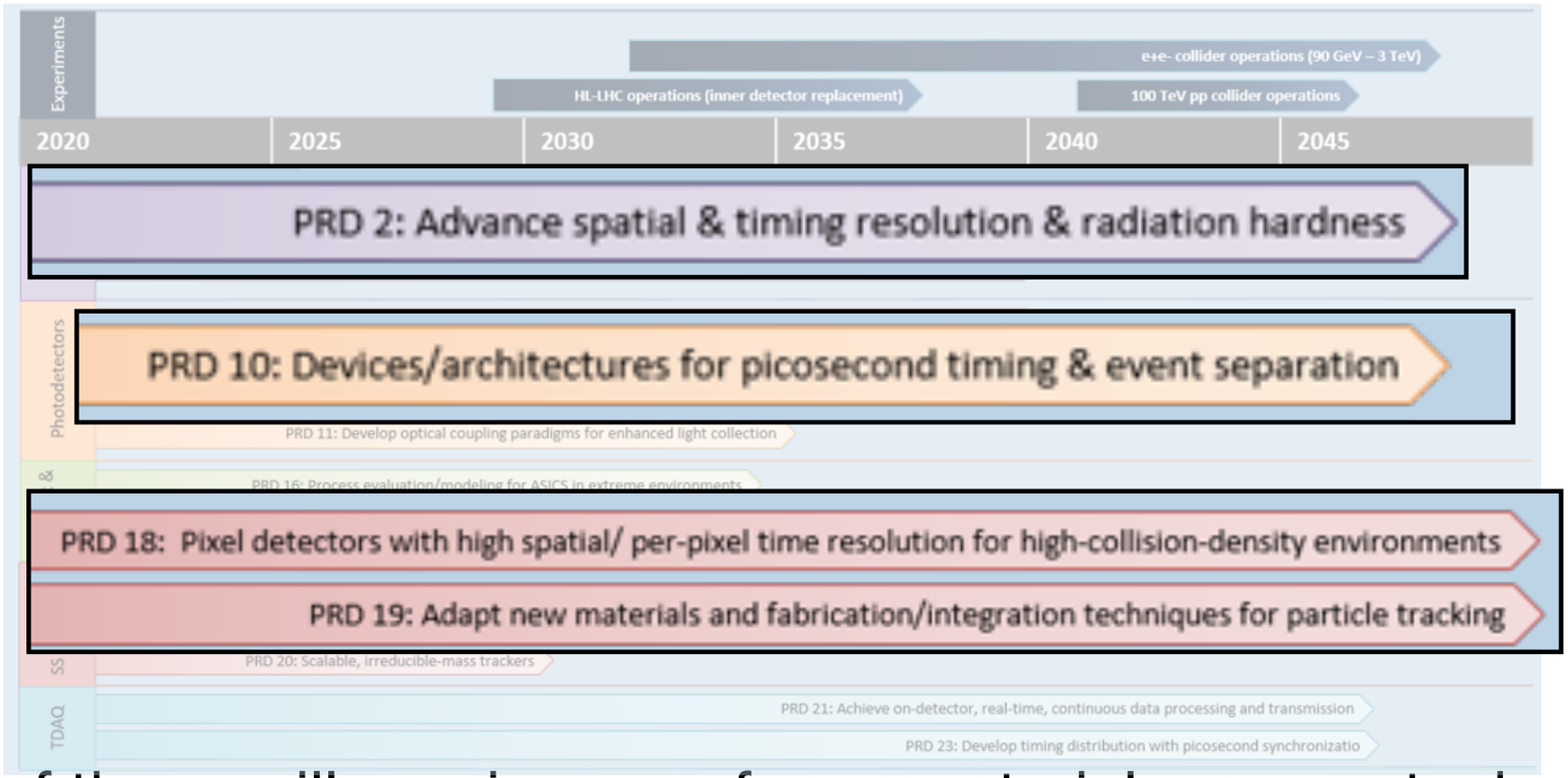
Timeline of Research Priorities for Higgs and Energy Frontier in BRN Study



Future Detector Development

Role of Test beam

- Test beam and irradiation facilities will continue to be critical to development of almost all of these these detector developments



- All of these will require use of new materials or new technologies, which will require continuous testing in a test-beam environment
- Test beams will also need to adapt and improve to meet the needs of the detector research

Test Beam

Increase User Base

- Training opportunities can be an effective way to engage new users
- LPC has had a good amount of success in engaging and recruiting new users through Hands-on Advanced Tutorial Sessions (HATS)
  - Typically half-day or one day tutorial, with hands-on exercises
  - Give new users experience in many aspects of CMS
    - Has been applied to both tools and frameworks for physics analysis, as well for detector upgrades and operations tasks
- I believe that incorporating such a training/tutorial session could be a useful tool in bringing in new users to the test beam facility at Fermilab
  - Simple hands-on examples and experiences can go a long way in demystifying the experience, engaging new users, and providing easy ways to get over the learning curves involved

Summary

- Current detector upgrade efforts on CMS have been very successful
  - I’ve had leading roles in the upgrades of the HCAL and HGCAL subdetectors
- Future detector development will be critical for continued success of the field in years to come
  - New accelerators and experiments will require continued development of detector technologies
  - Fermilab Test Beam Facility and Irradiation Test Area will continue to play a crucial role in these projects into the future
- I believe my experience in detector development, testing, and integration would allow me to make a positive impact within the Fermilab Test Beam group

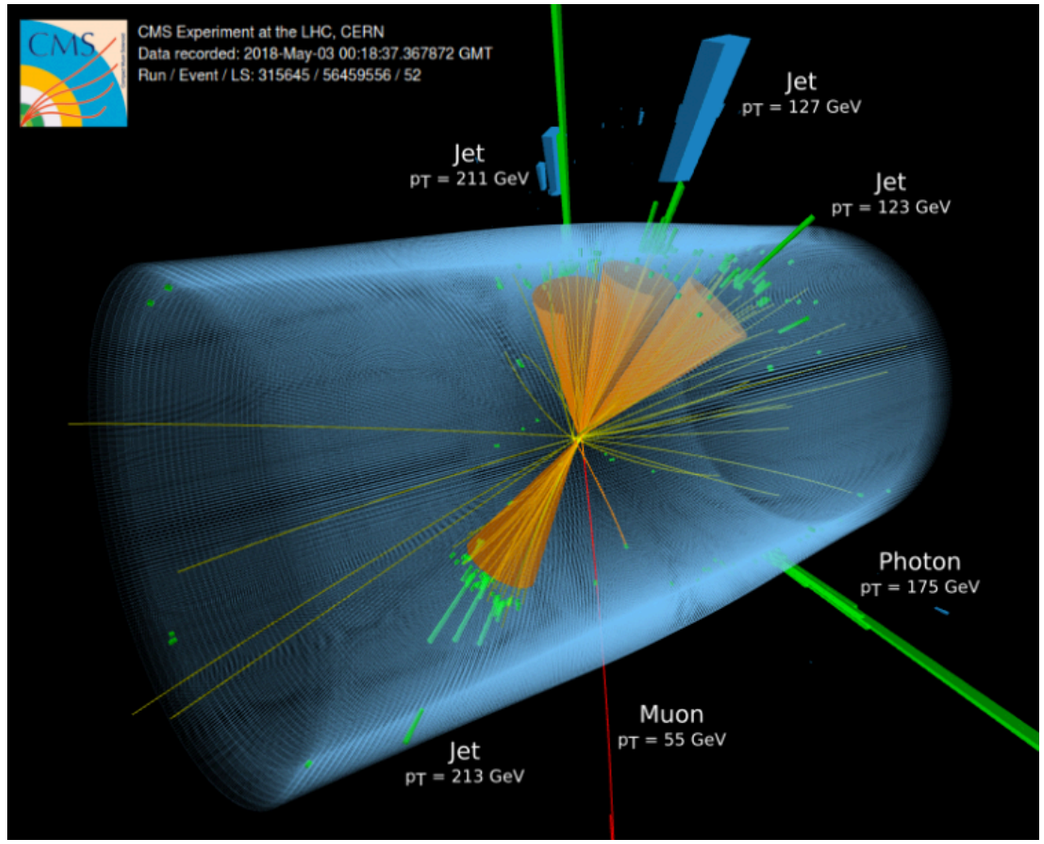
Backup

Physics Analysis

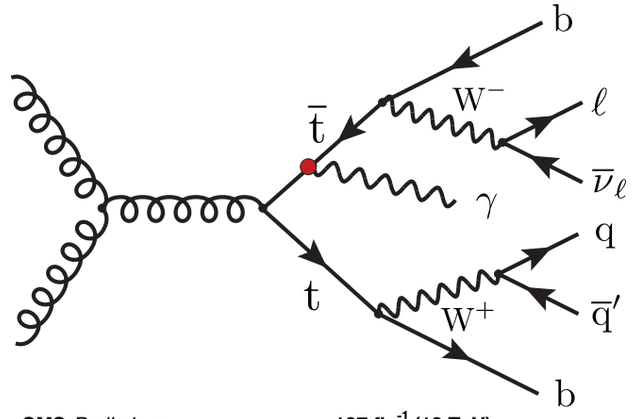
tt+γ cross section measurement

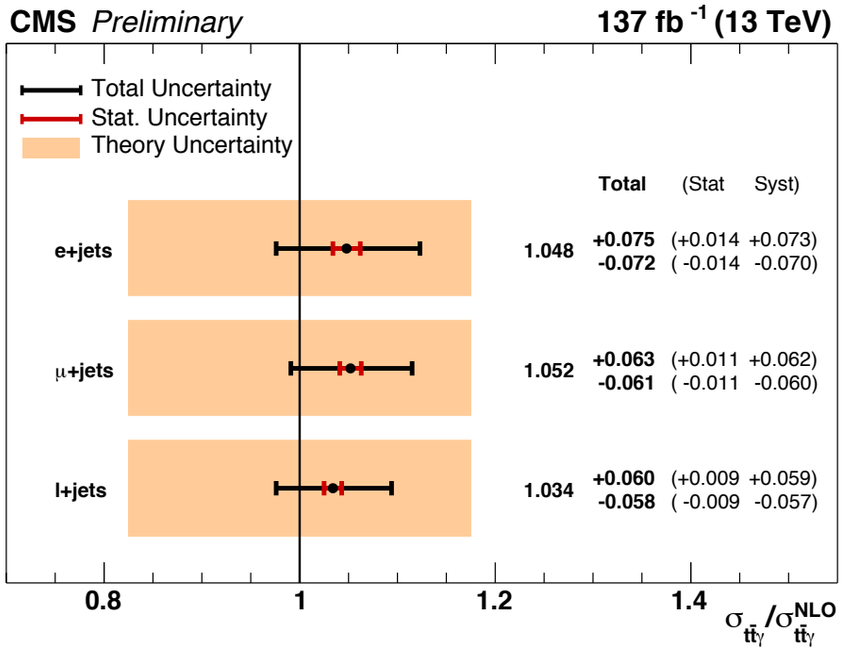
- Top quark pair production with a photon
  - Measured in semileptonic final state using full Run 2 dataset from CMS
- Measurement of both the inclusive and differential cross section

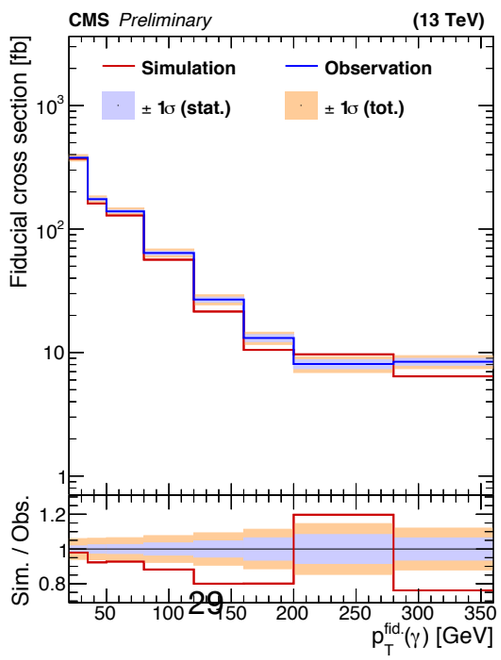
$$\sigma_{\text{fid}}\,(\text{tt}\gamma) = 800 \pm 46\ (\text{syst}) \pm 7\ (\text{stat})\ \text{fb}$$

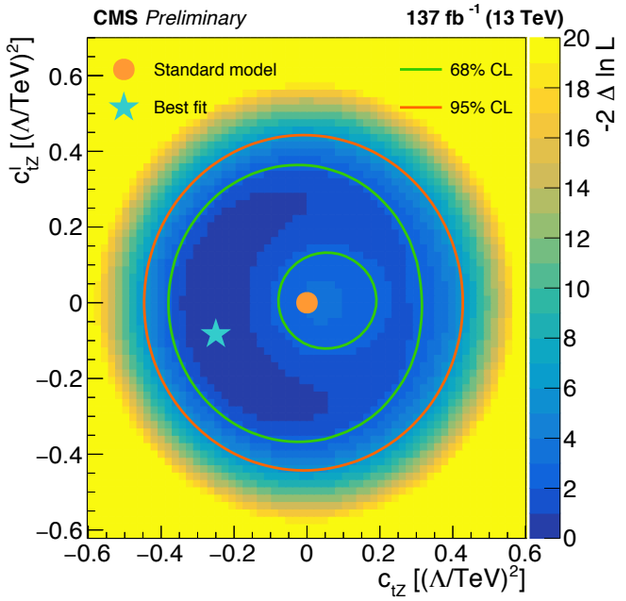


- Sensitive to electromagnetic coupling of the top quark
  - Results can be interpreted to constrain EFT coefficients which affect the top-photon interaction





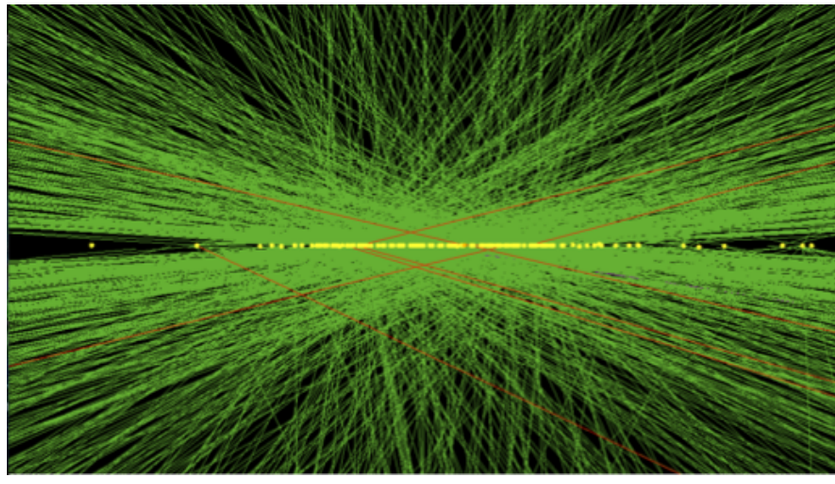


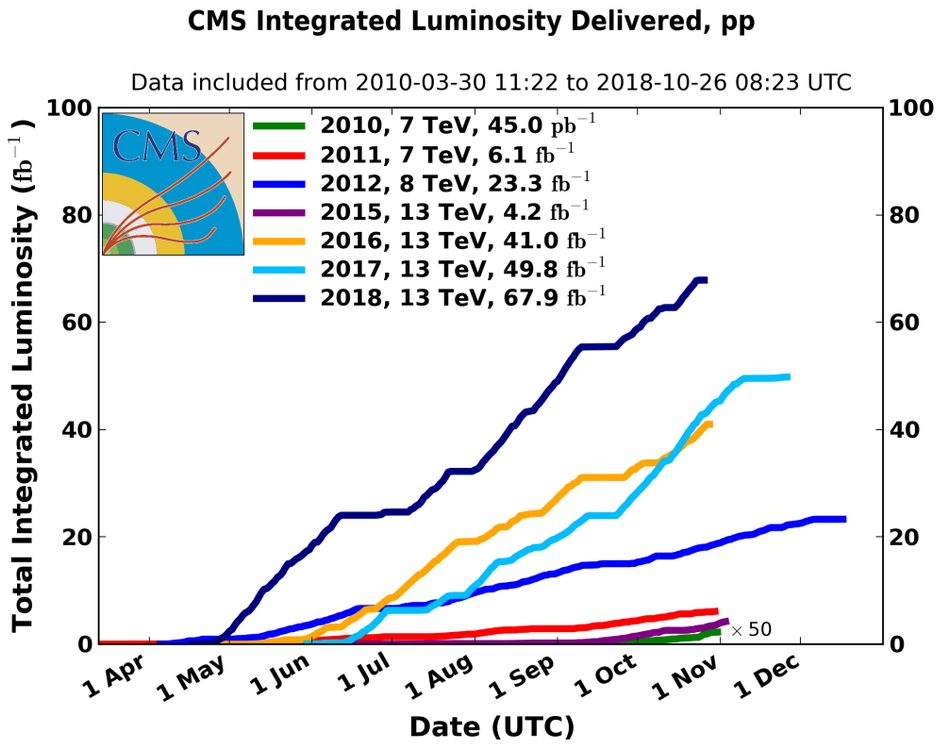


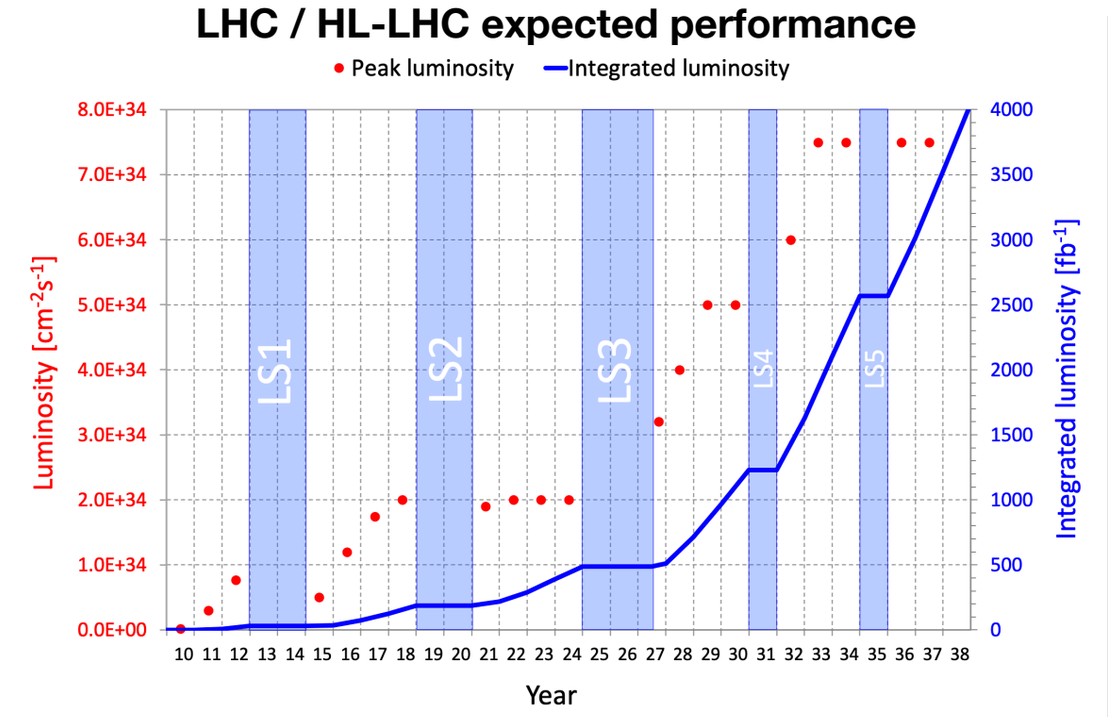
LHC Performance

- LHC has been performing beyond expectation
  - Performance has been improving year over year
- High Luminosity LHC (HL-LHC) will allow higher rates
  - Factor of 5-7 times the design luminosity of the LHC
  - Up to 200 interactions per bunch crossing
- Upgrades required to the CMS detector to cope with the higher rates and accumulated radiation damage

Simulated HL-LHC collision event

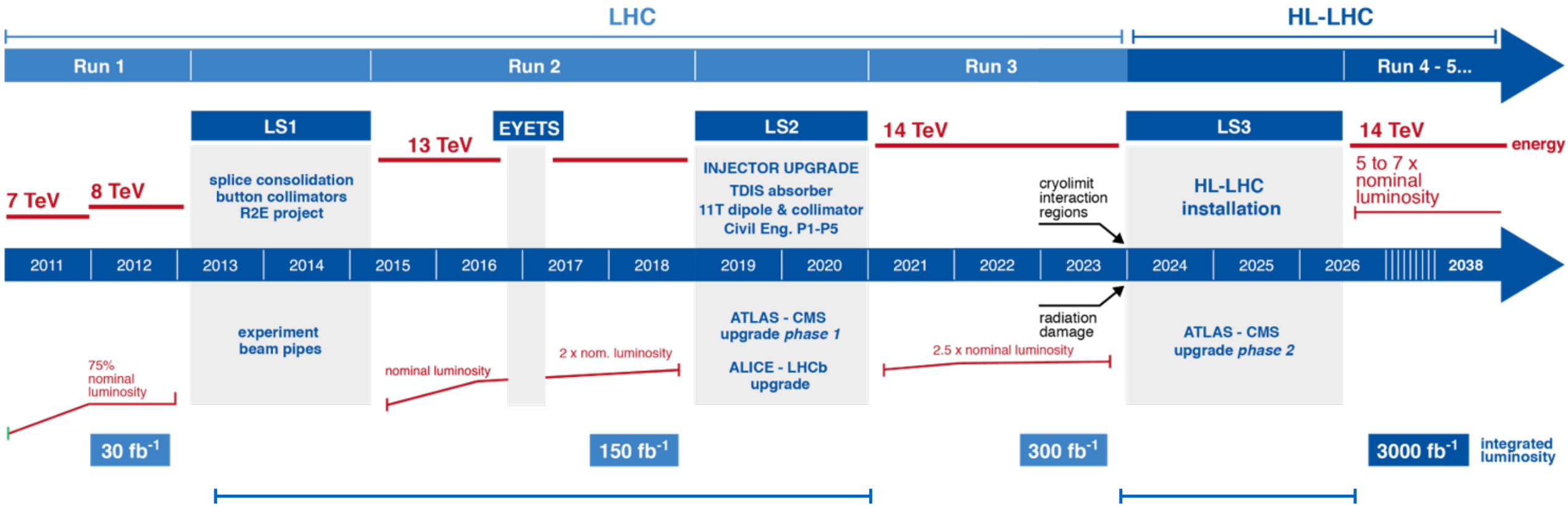






CMS Detector Upgrades

- CMS Update program split into two regimes:
  - Recently completed Phase-1 Upgrades
  - HL-LHC Upgrades to be installed after Run 3



Phase-1 Upgrades

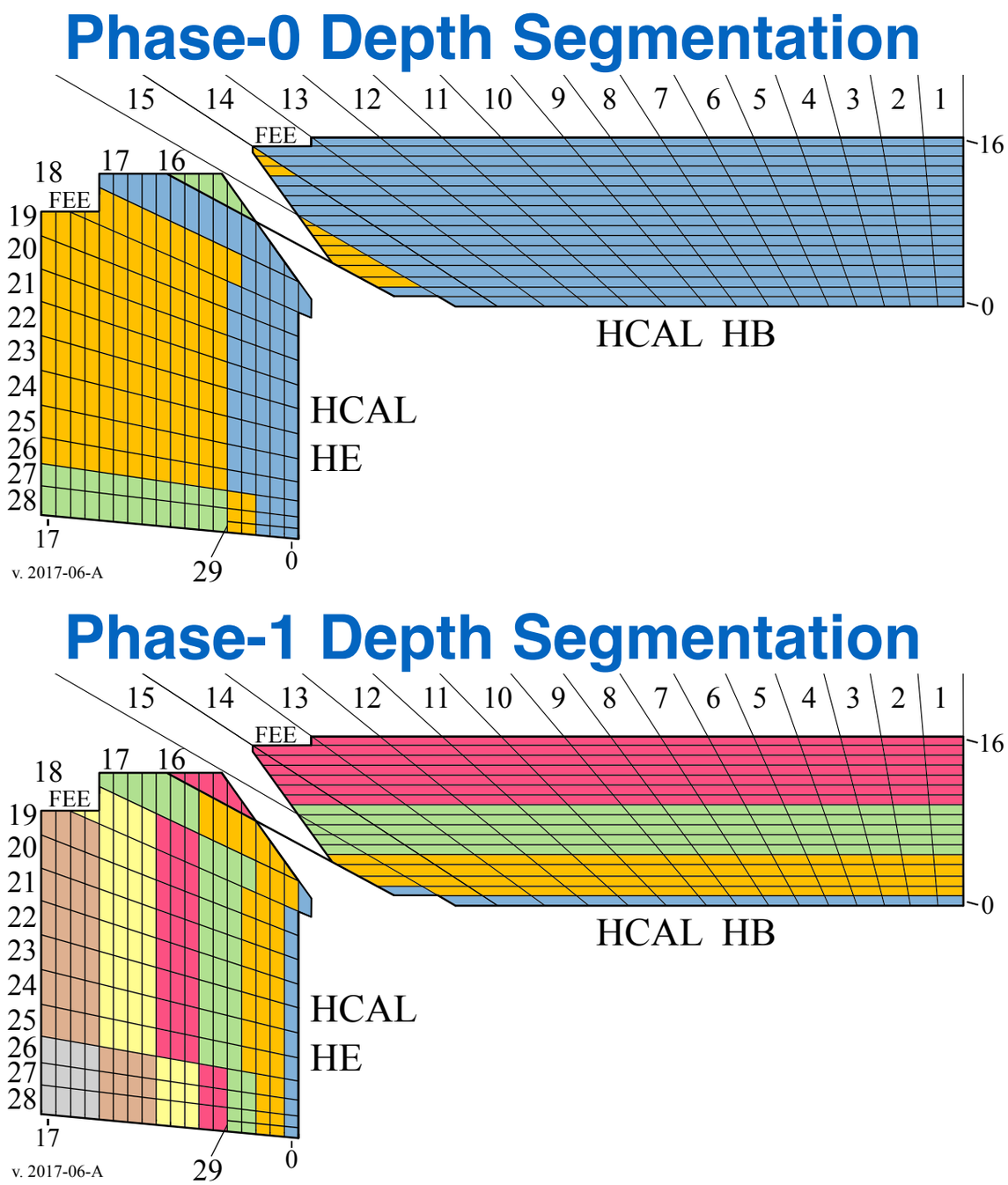
Improvements to specific subsystems to keep CMS running smoothly through Run 3

HL-LHC Upgrades

Upgrades of most of CMS to cope with HL-LHC running environment

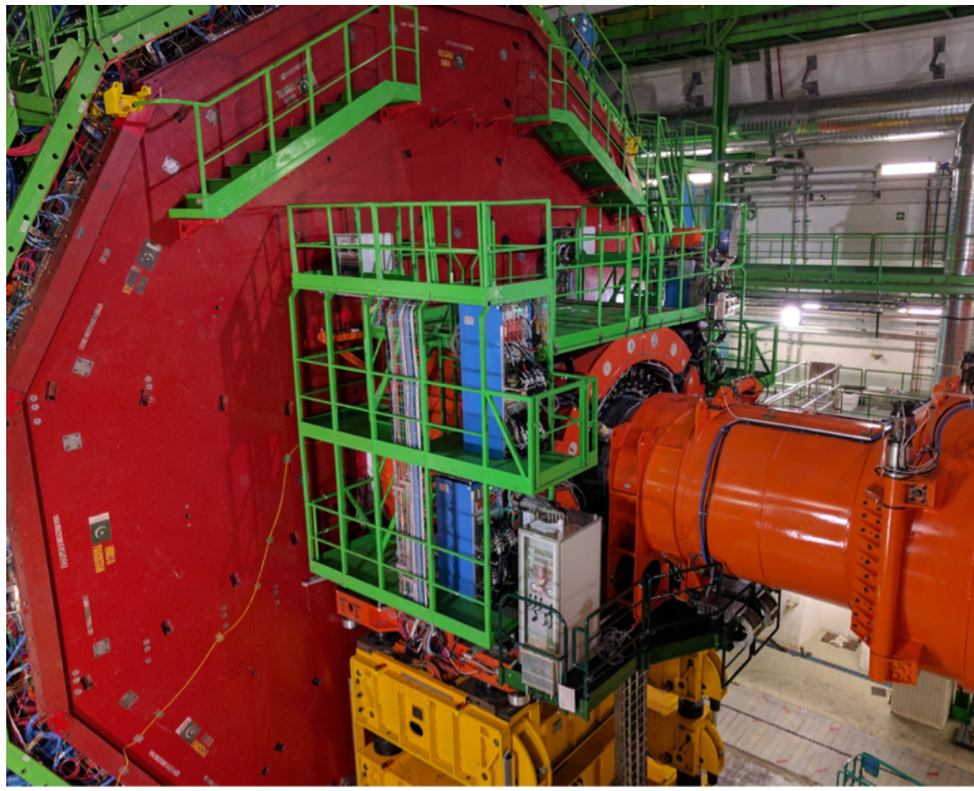
HCAL Phase-1 Upgrades

- **Upgrade Motivation**: Noise and radiation damage cause degradation of the detector
- **Forward (HF)** : Cherenkov calorimeter, steel absorber with quartz fibers feeding light into PMT
  - Replacement of PMT's,
  - New front end electronics with timing information
- **Endcap (HE) / Barrel (HB)** : Sampling calorimeter brass / plastic scintillator layers
  - Replacement of photodetectors
  - New front end electronics with more channels; better depth segmentation
  - More precise calibration of depth-dependent radiation damage
- **New front-end electronics** feature QIE10 and QIE11 ASICs,
  - Designed by Fermilab, tested and calibrated with university partners

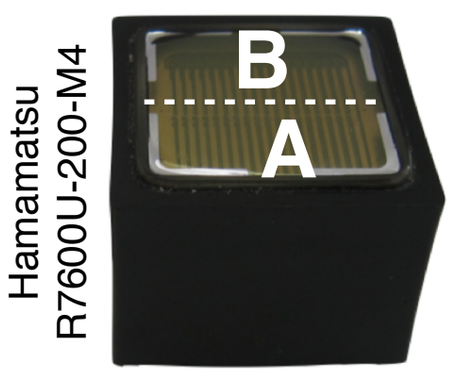


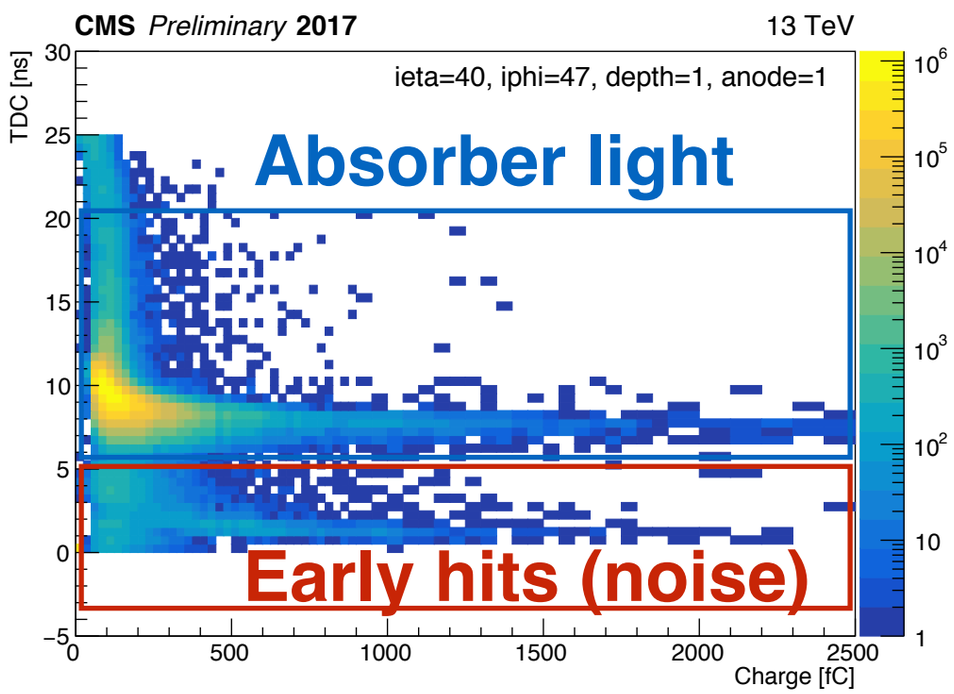
HCAL Upgrades

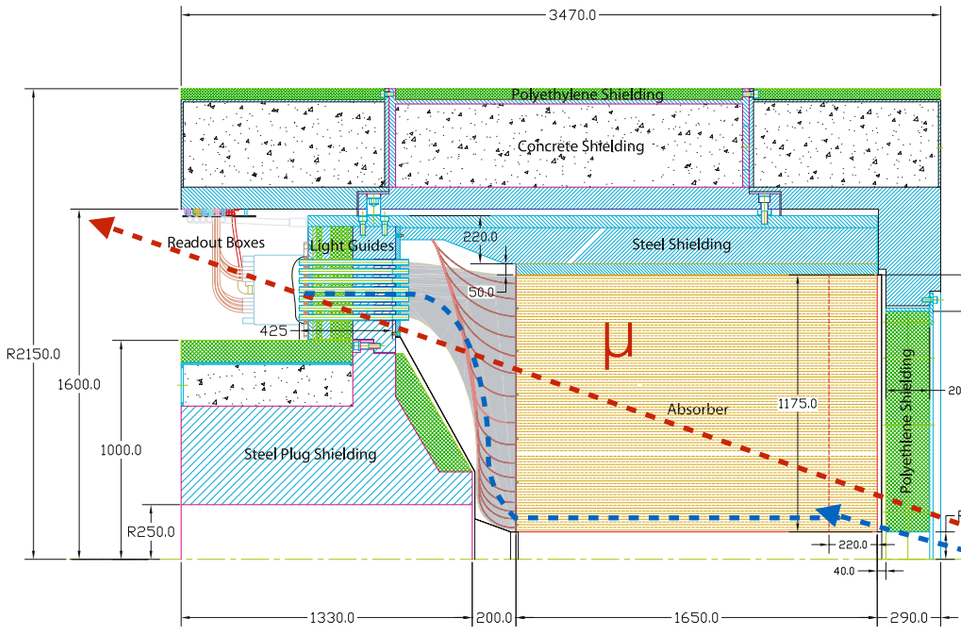
Forward Hadronic Calorimeter (HF)



- Significant background noise from anomalous hits in the PMT's themselves
- Upgrade to the electronics and replacement of PMT's
  - PMT's readout in dual anode mode, thinner window
  - New electronics provide timing information critical for noise rejection

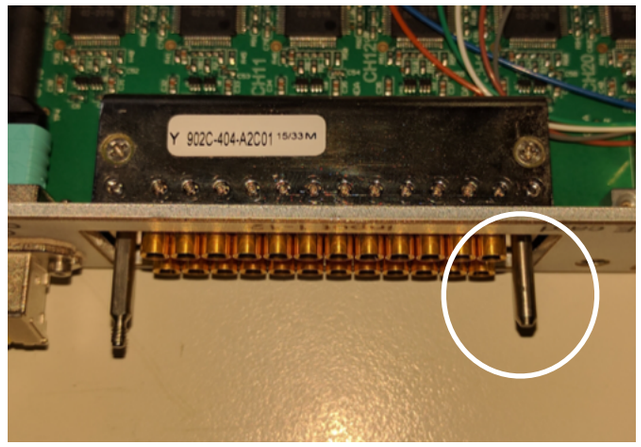




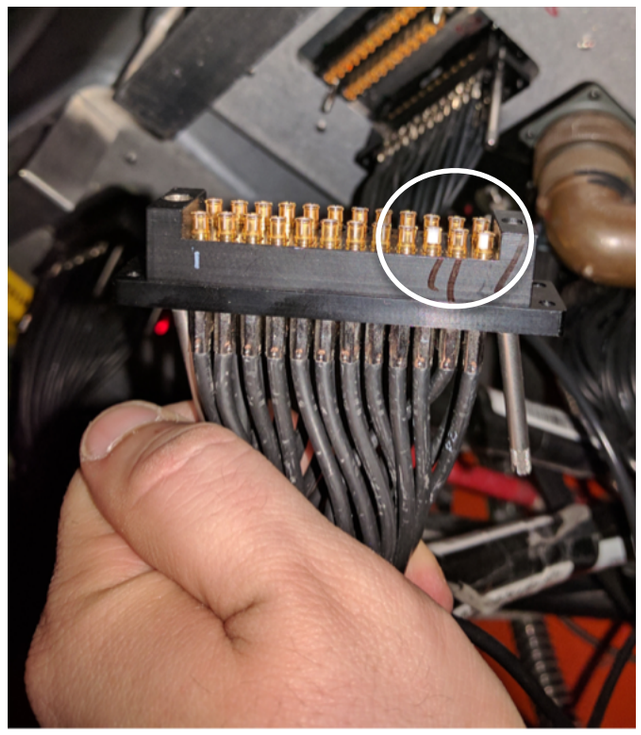


HF Commissioning and Installation

- Numerous issues encountered and remedied over the course
  - Mismatch in DC/DC supply voltage on circuit

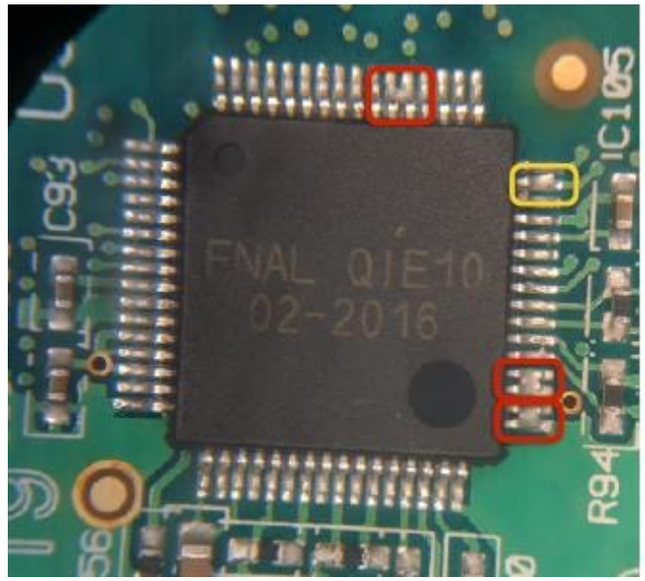


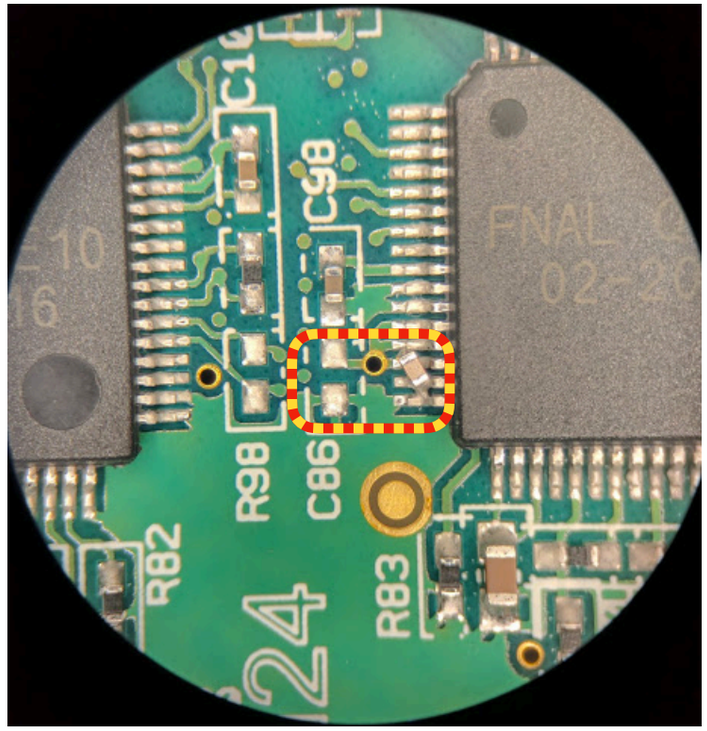
  - Quality issues in initial assembly
  - Fragility of cables and connectors (custom cables, consisting of 24 coaxial cables)



HF Commissioning and Installation

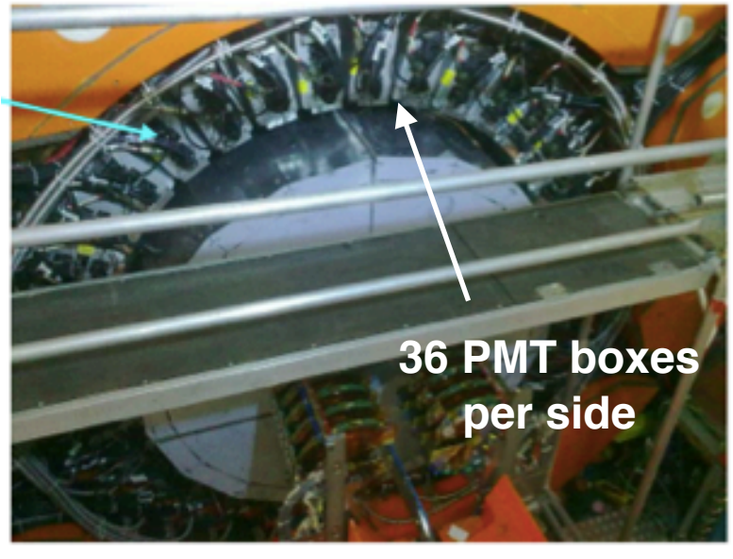
- During spring of 2016, full replacement of QIE ASICs undertaken on previously assembled boards
  - Fix a small issue discovered in the ASIC
- Problems with the rework quality seen in first two batches
  - Unsoldered pins, missing components, shorted pins
  - 23 of 40 boards failed visual inspection
- Assembler was immediately contacted upon seeing the problems, and QC was improved
- No problems observed in further batches

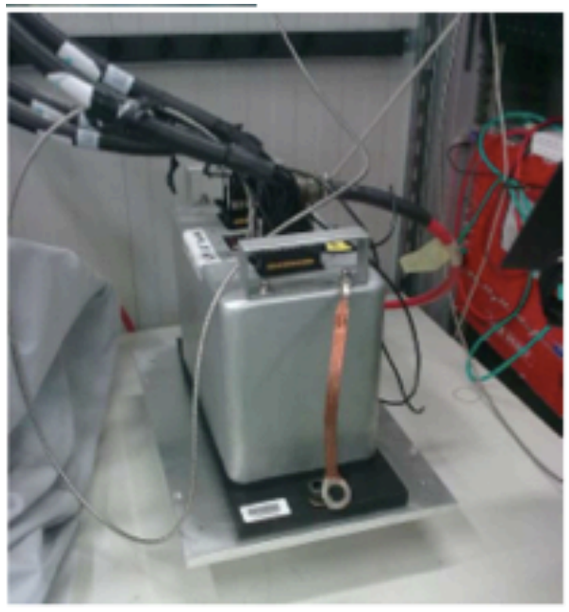


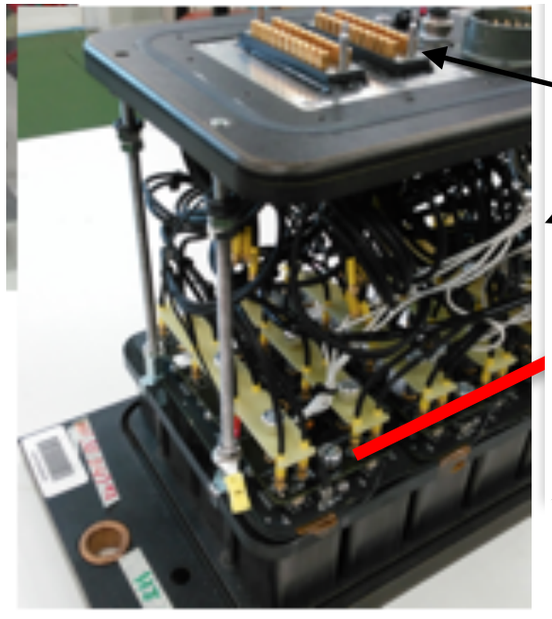


HF PMT Rework

- PMT's we are using have 4-anodes
- Since LS1, PMT's have been read out as a single channel (anodes joined together)
  - **Adapter board**: connects to PMT base board and gangs anodes into output channels
- Rework of PMT boxes splits signal into dual anode readout
  - Replacing adapter board to go from 1-channel readout to 2-channel (dual-anode) readout



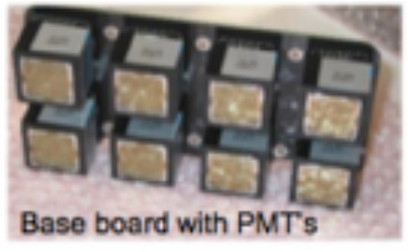




Connection from adapter board to cable to front end

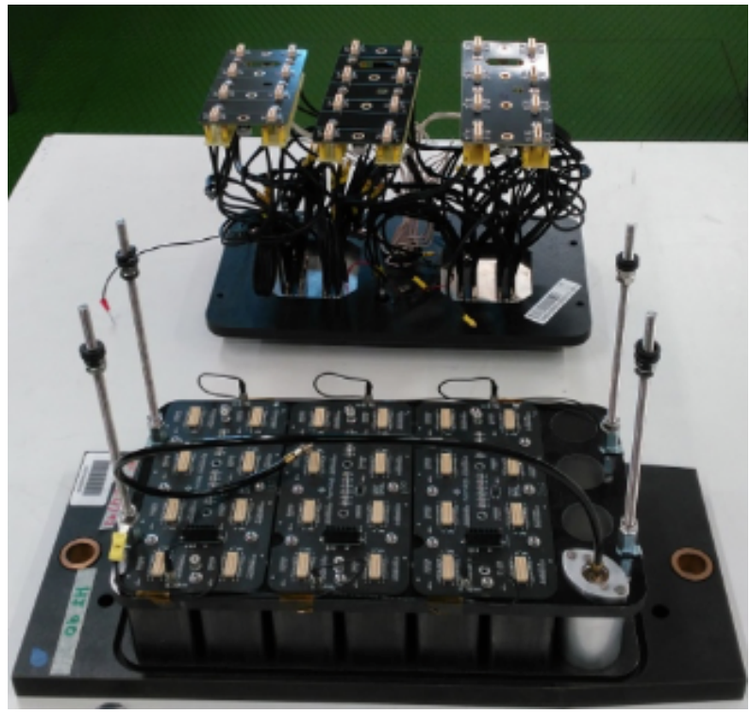
Adapter Board

PMT Base Board



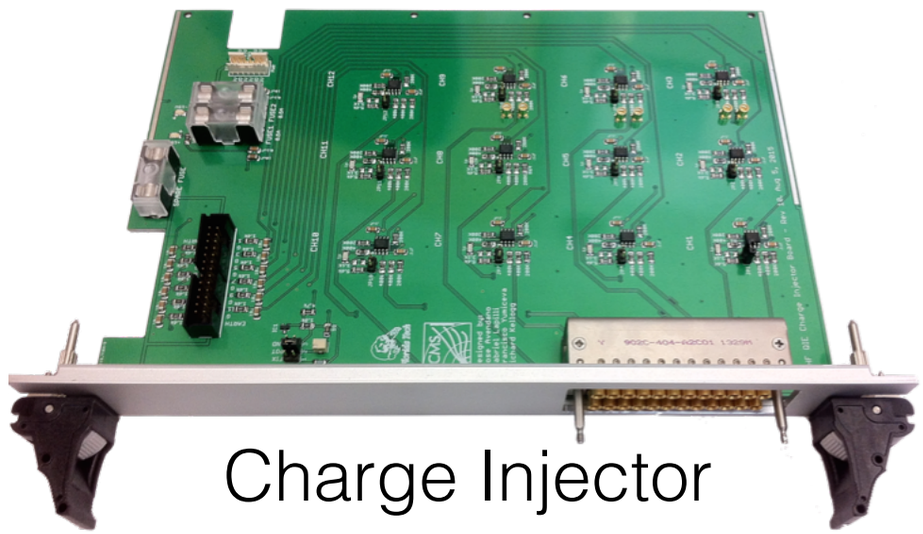
HF PMT Rework

- PMT boxes removed from detector and brought to surface
  - Rework performed in SX5
- Procedure:
  - Boxes tested before rework (measure LED light pulses)
  - Open PMT box
  - Change Adapter Board
  - Electrical and mapping test
  - Close box
  - Retest with LED, sign-off on boxes after passing all tests
- PMT boxes installed back on detector after rework

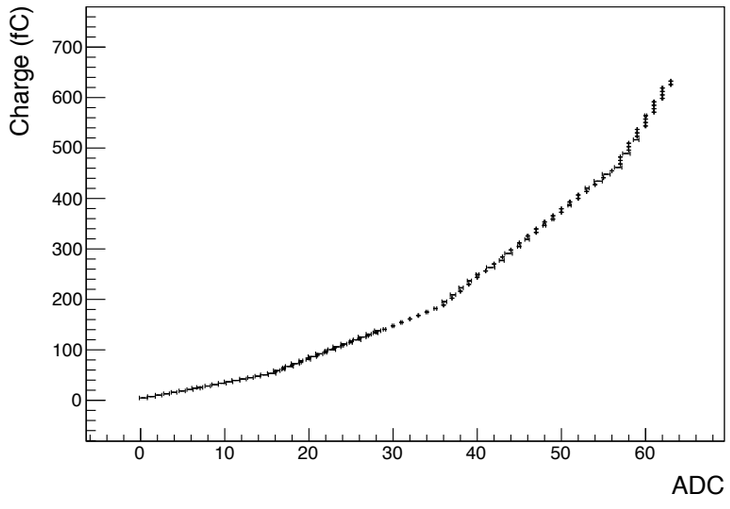


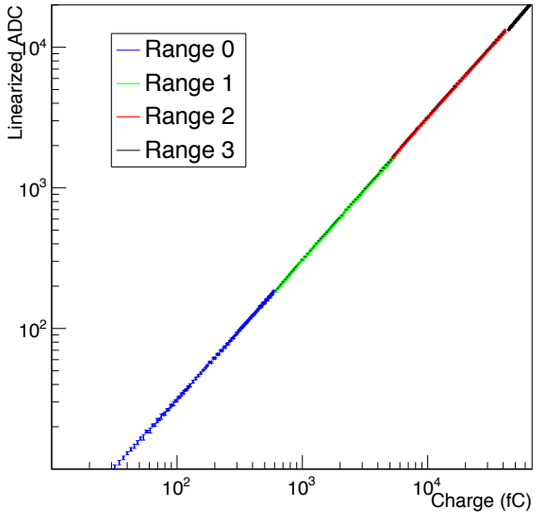
HF Calibration

- Provides the calibration conditions necessary for converting QIE10 ADC measurements back to charge
- External charge injector built to supply precise current into QIE cards
  - Can measure ADC response of QIE cards at large range of injected charge
  - Configurable through 16-bit USB-controlled DAC
  - Provides injected charge in the range of +100 fC to -50 pC
- Individually calibrate each range and capID on every QIE10



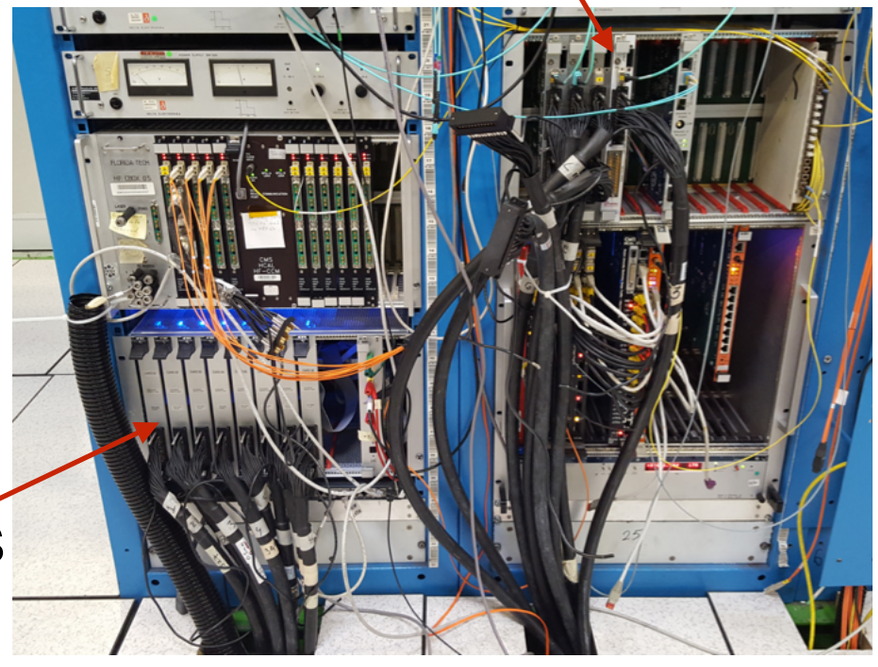
Charge Injector





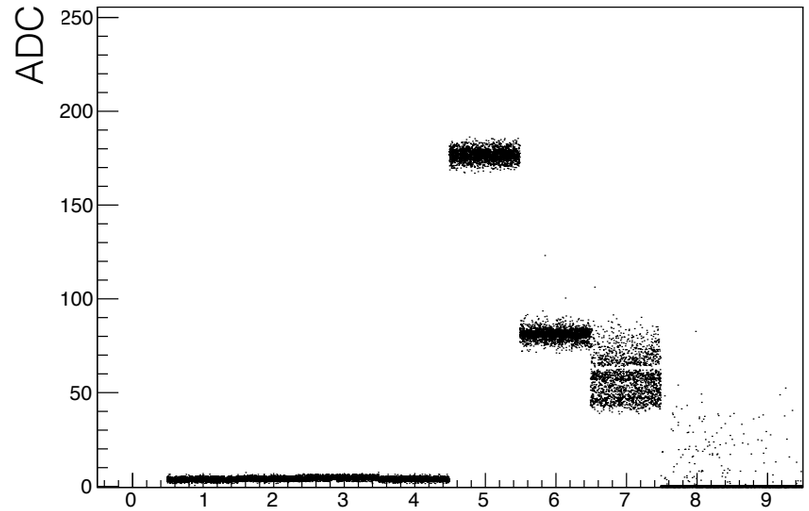
QIE10's being calibrated

Charge Injectors

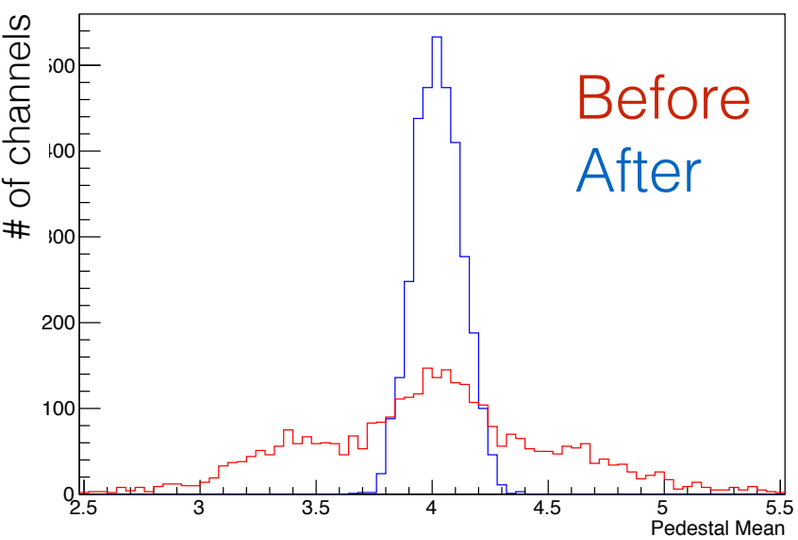


HF Commissioning

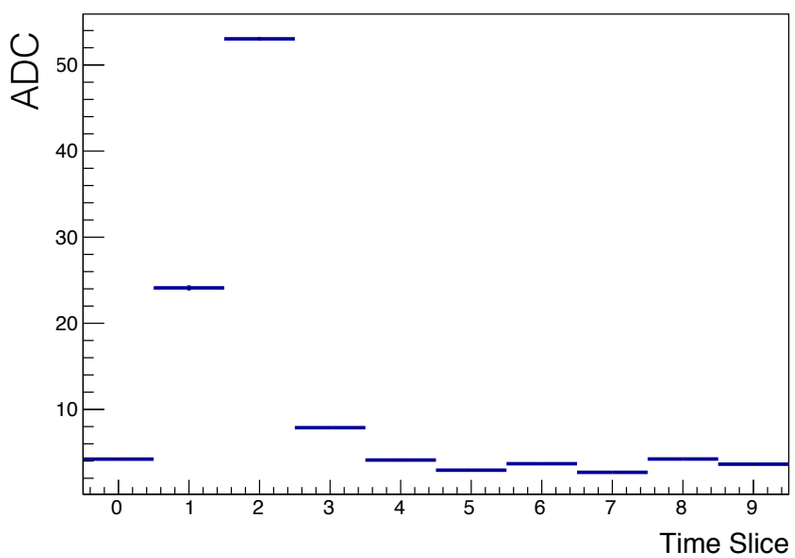
- Local runs used to commission the detector
  - Measuring Pedestal
  - Internal Charge Injection (QIE has ability to inject pulse internally)
  - LED pulse: inject light pulse into PMT box from calibration unit
  - Laser: inject pulse simultaneously across system



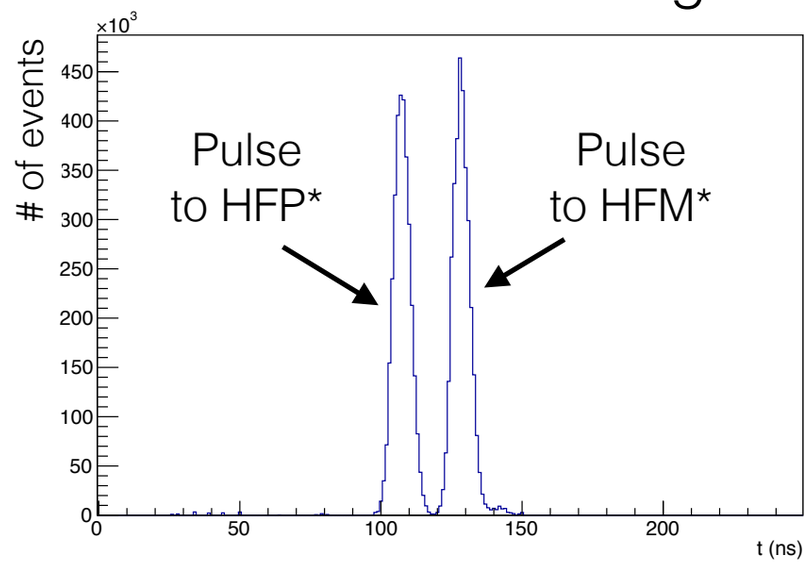
Pedestal Tuning



Laser Pulse

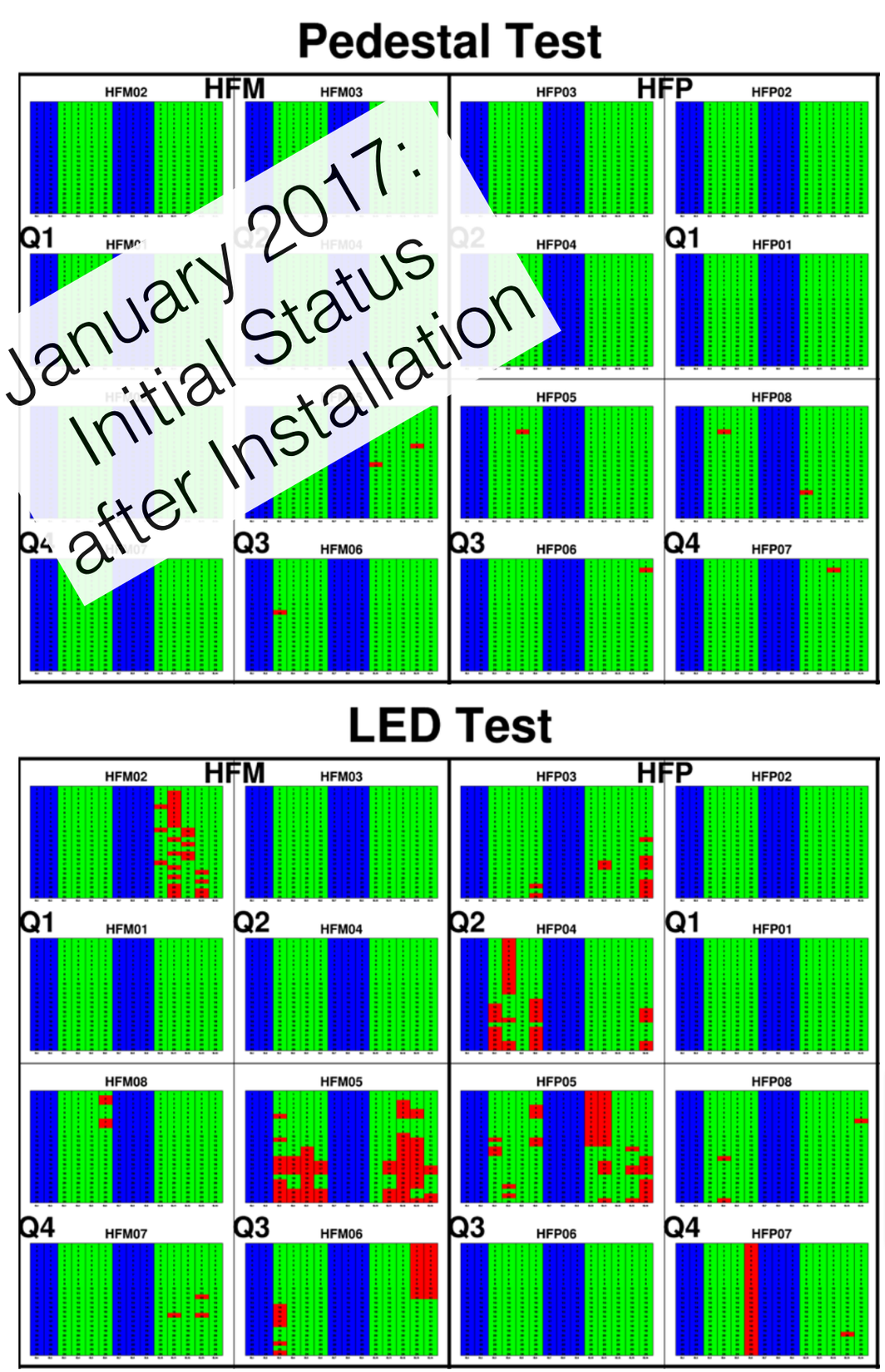


Laser Pulse Timing



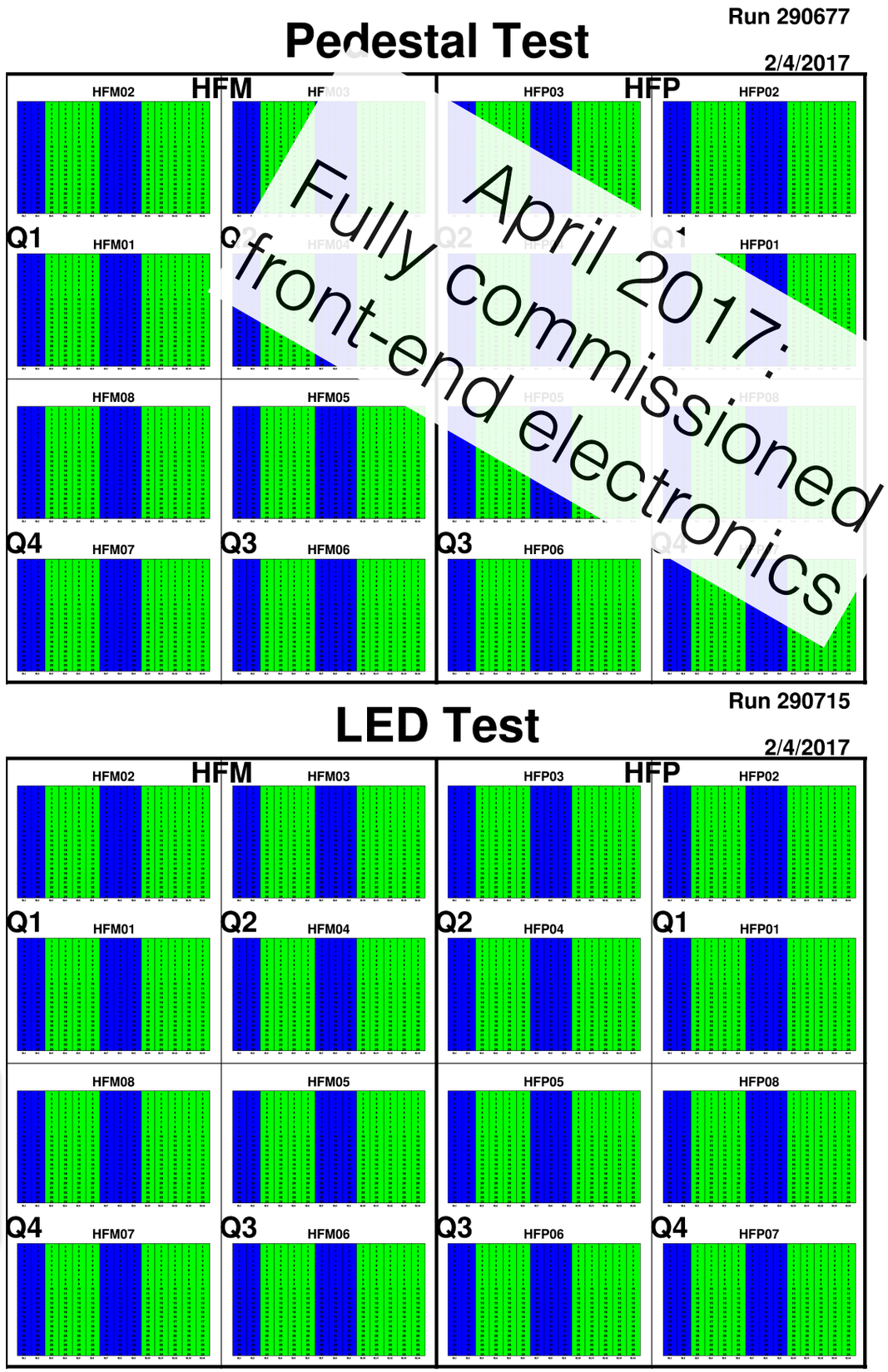
* Different laser fiber lengths to HFP and HFM

Detector Commissioning



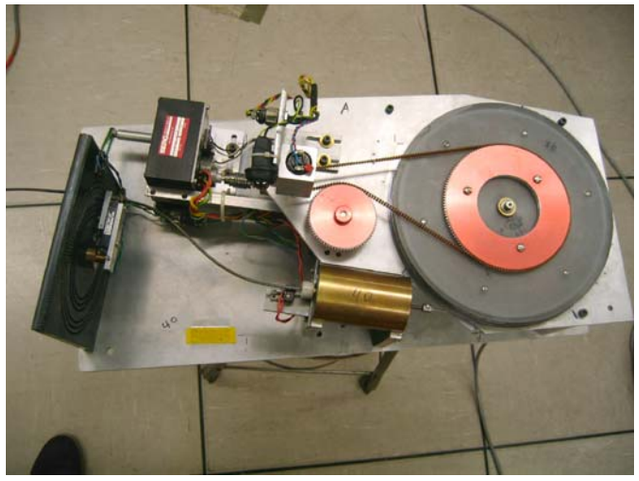
Reconnect/replace cables
Replace bad cards

Good Channel
Bad Channel
Empty Channel

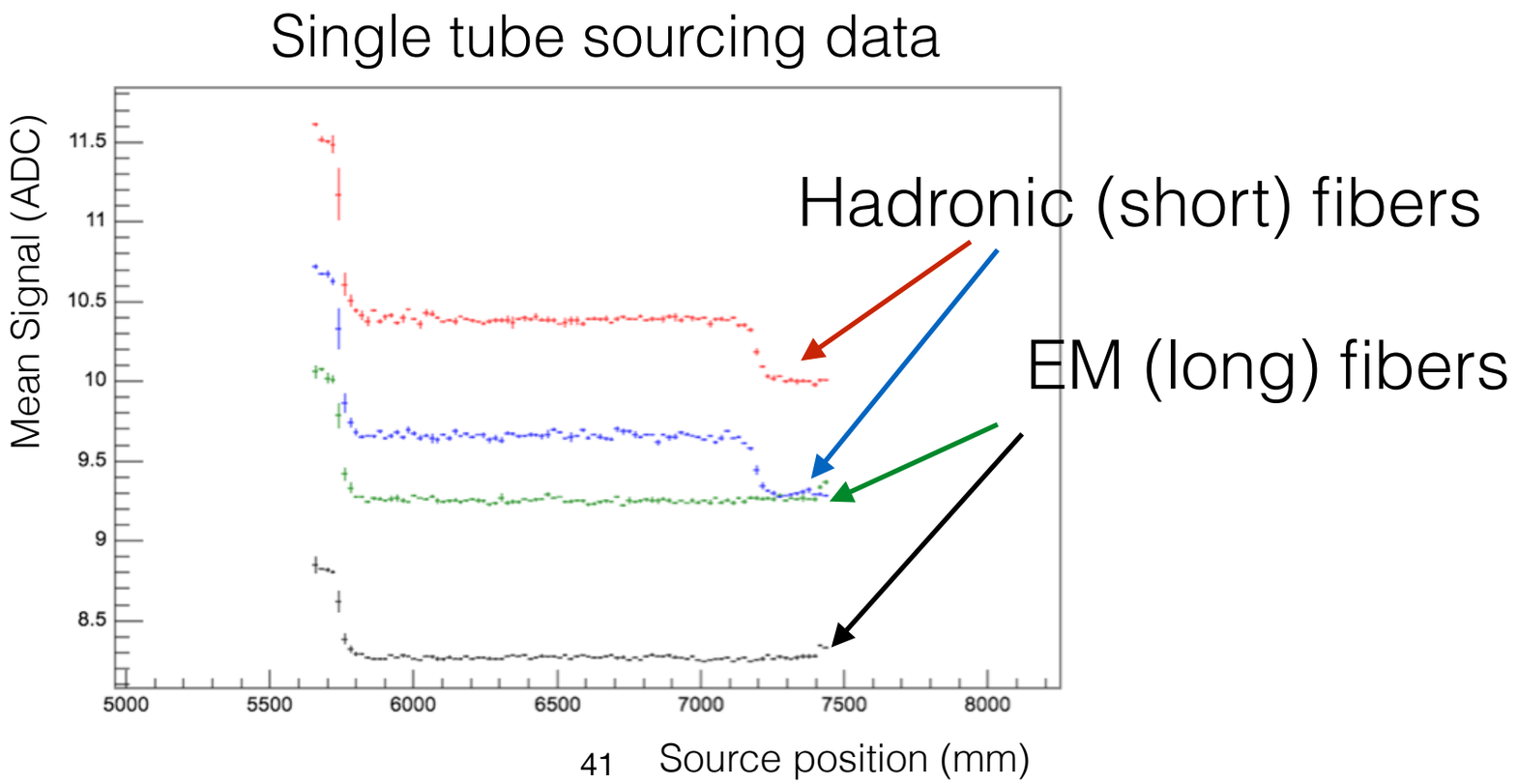


HF Sourcing Calibration

- Source driver to move wire with Co-60 source through detector
- Each tower has one or two sourcing tubes
  - 31 tubes per wedge (20° in phi)
- Took around 18 hours per quarter of detector
- Used to verify channel mapping (from detector to backend) as well as future calibration

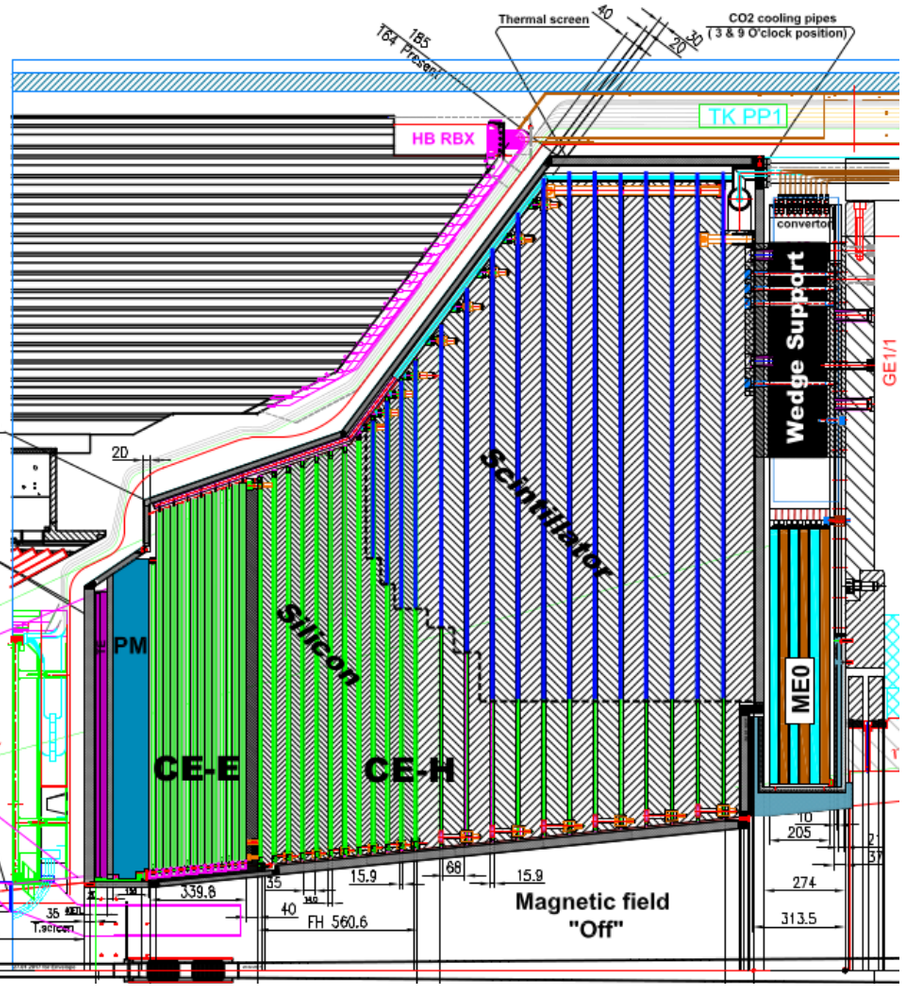


HF source driver

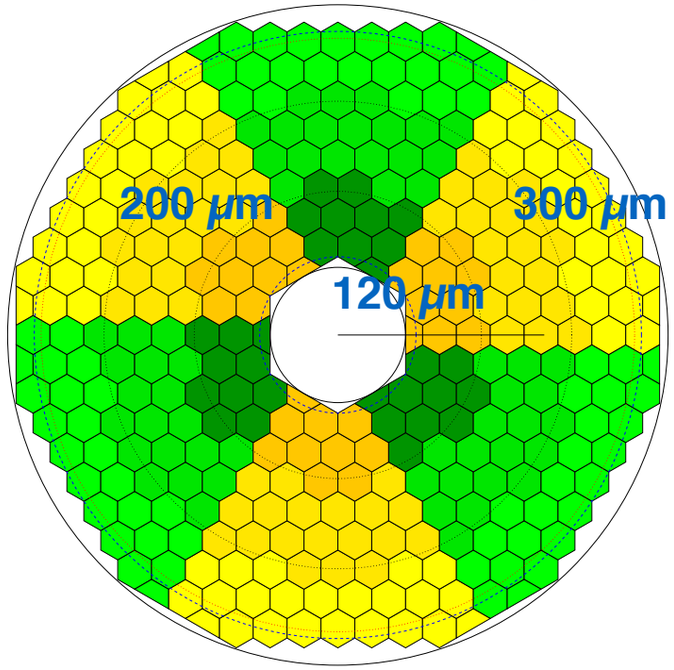


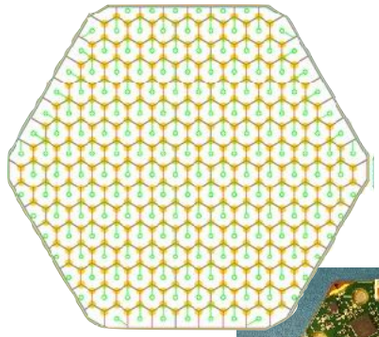
High Granularity Calorimeter

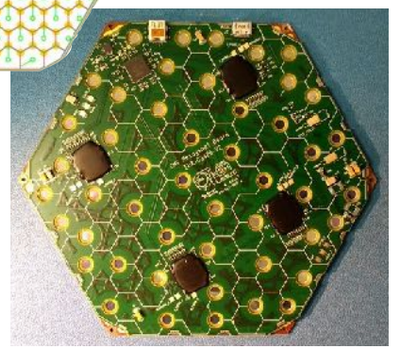
- Complete replacement of current end-cap calorimeters to handle



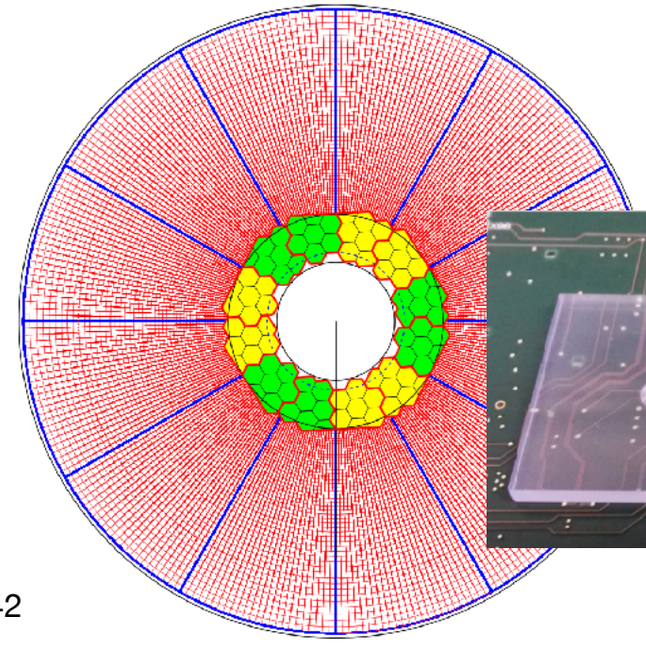
All-silicon layer

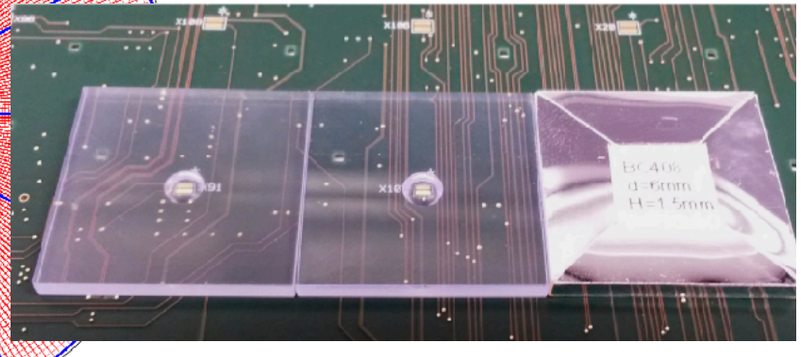






Silicon/scintillator layer

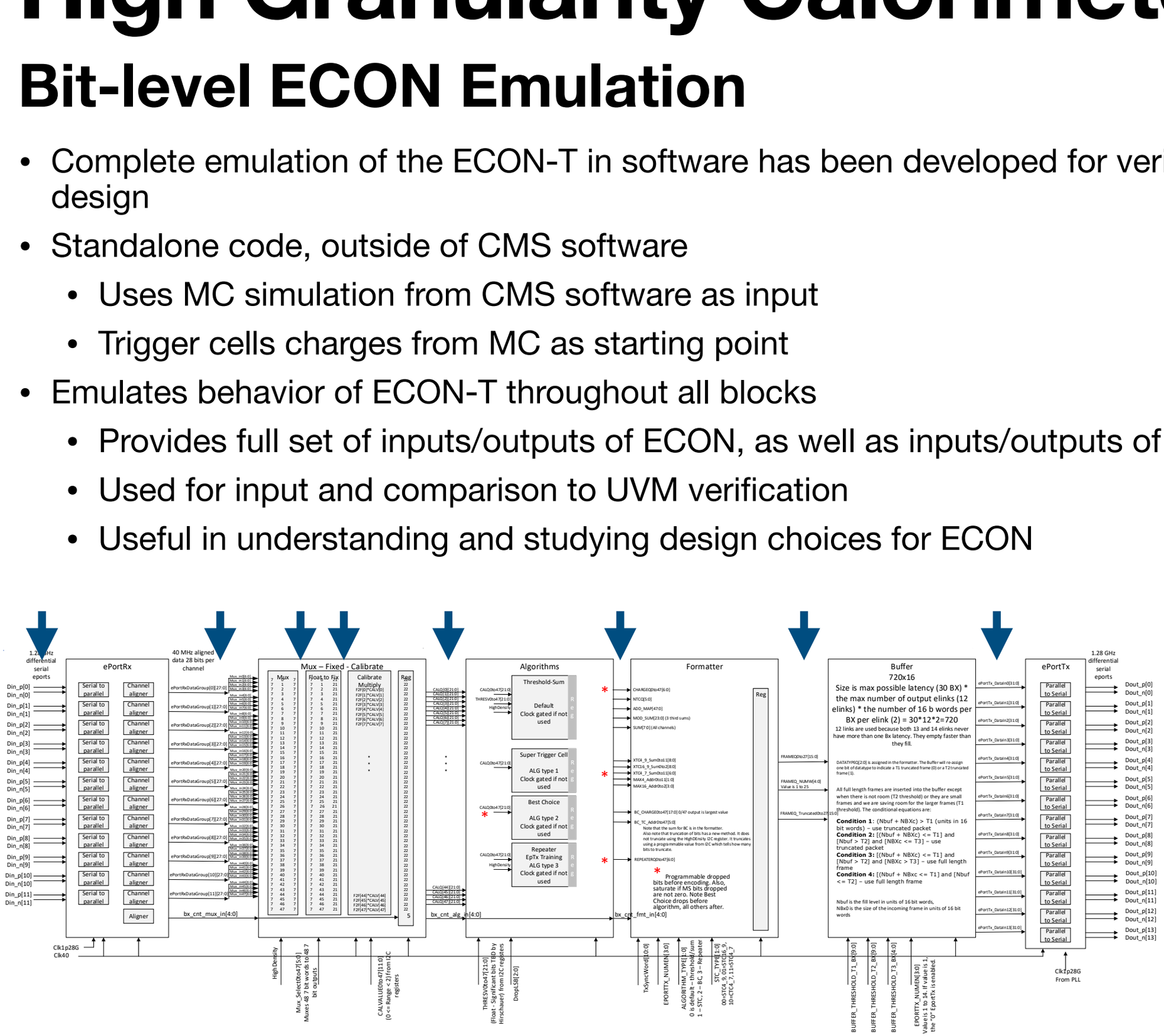




High Granularity Calorimeter

Bit-level ECON Emulation

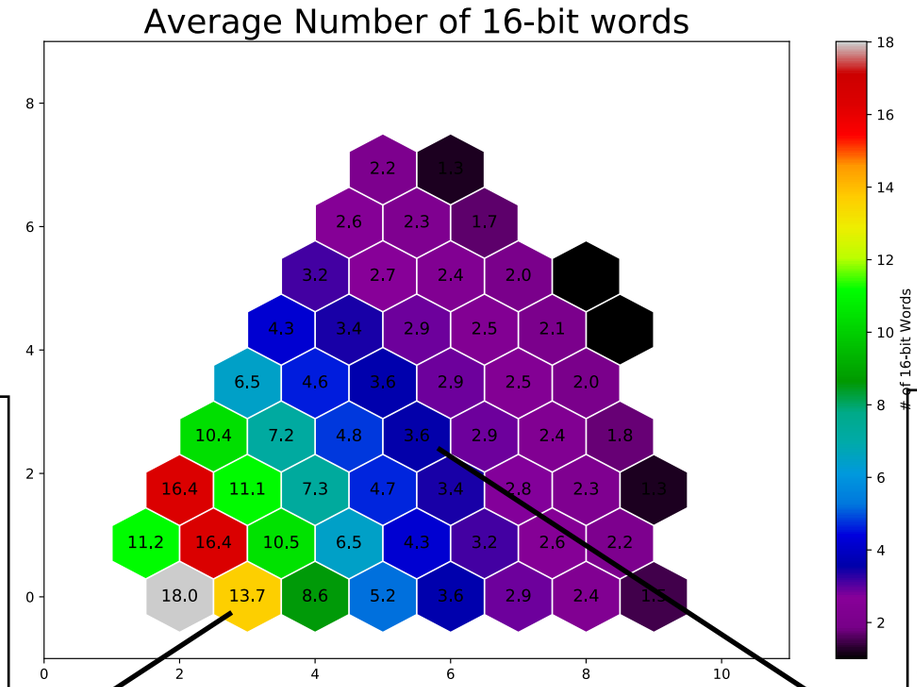
- Complete emulation of the ECON-T in software has been developed for verification of the design
- Standalone code, outside of CMS software
  - Uses MC simulation from CMS software as input
  - Trigger cells charges from MC as starting point
- Emulates behavior of ECON-T throughout all blocks
  - Provides full set of inputs/outputs of ECON, as well as inputs/outputs of each block
- Used for input and comparison to UVM verification
- Useful in understanding and studying design choices for ECON

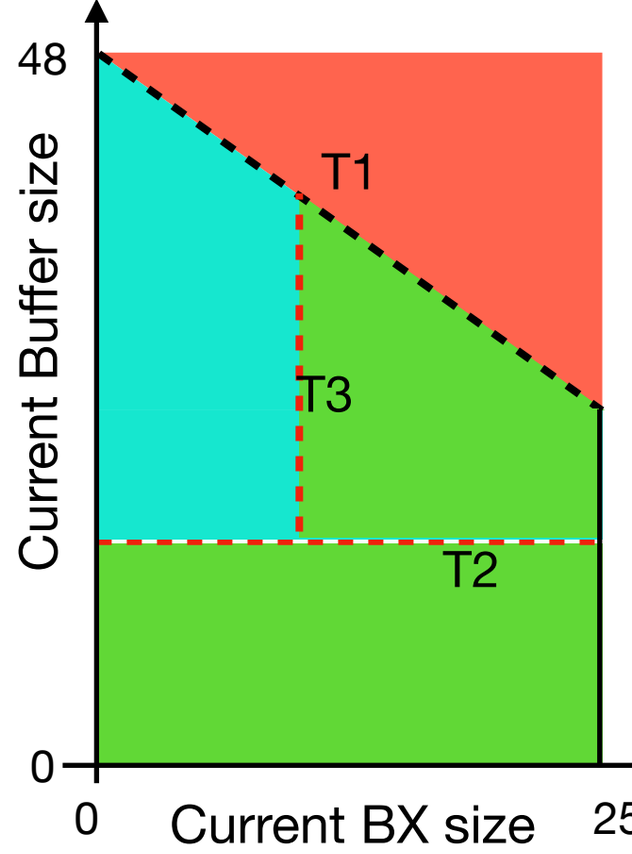


Expected values of all data saved at each point

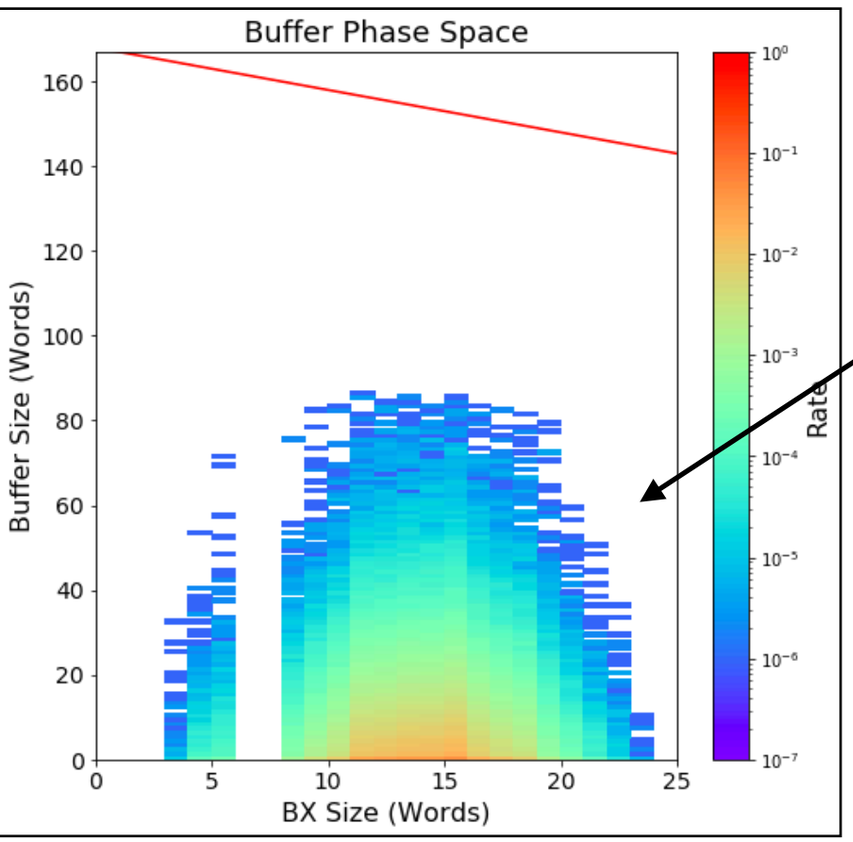
Buffer Study

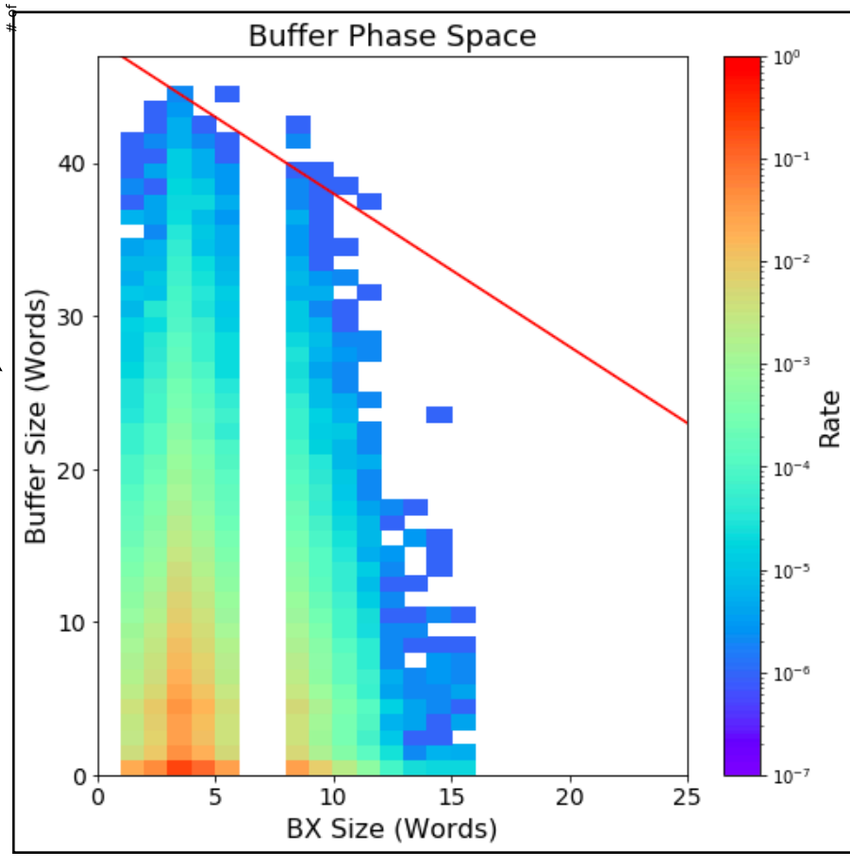
- Simulate buffer size with no buffer controls other than T1 (cannot go over max size)
- Look at phase space of Buffer size and current event size





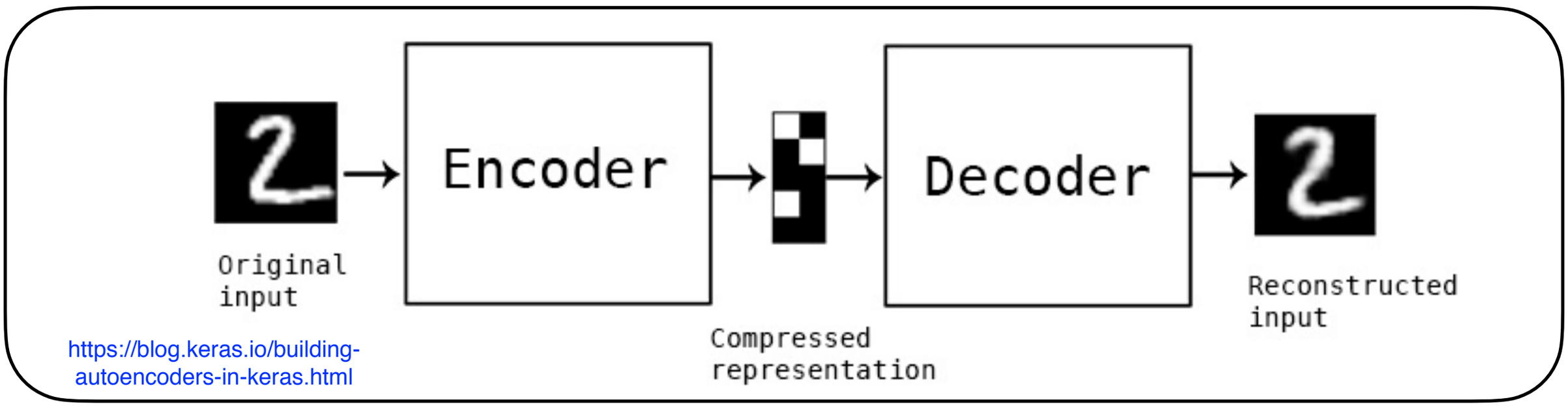
Module used for latency control scan on next slide

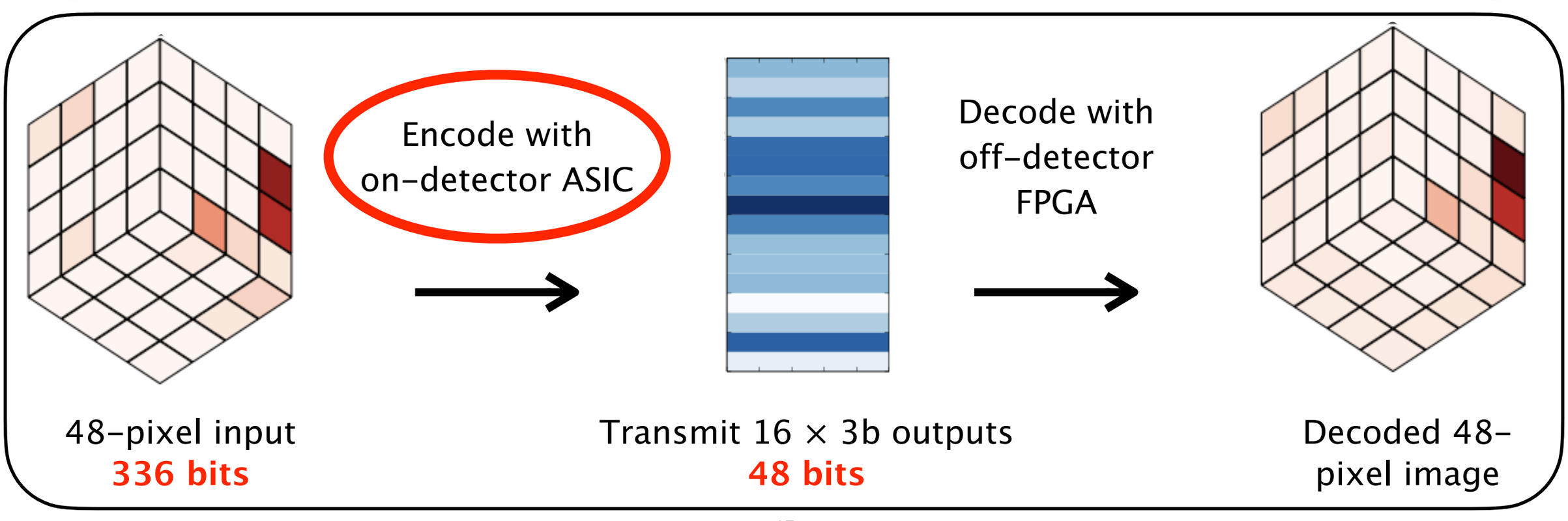




High Granularity Calorimeter

AutoEncoder Concept

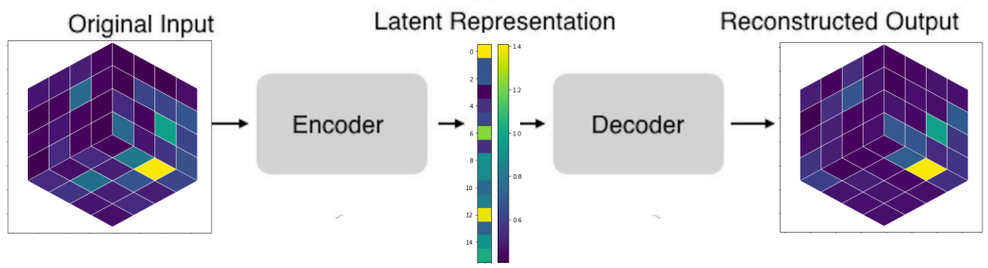




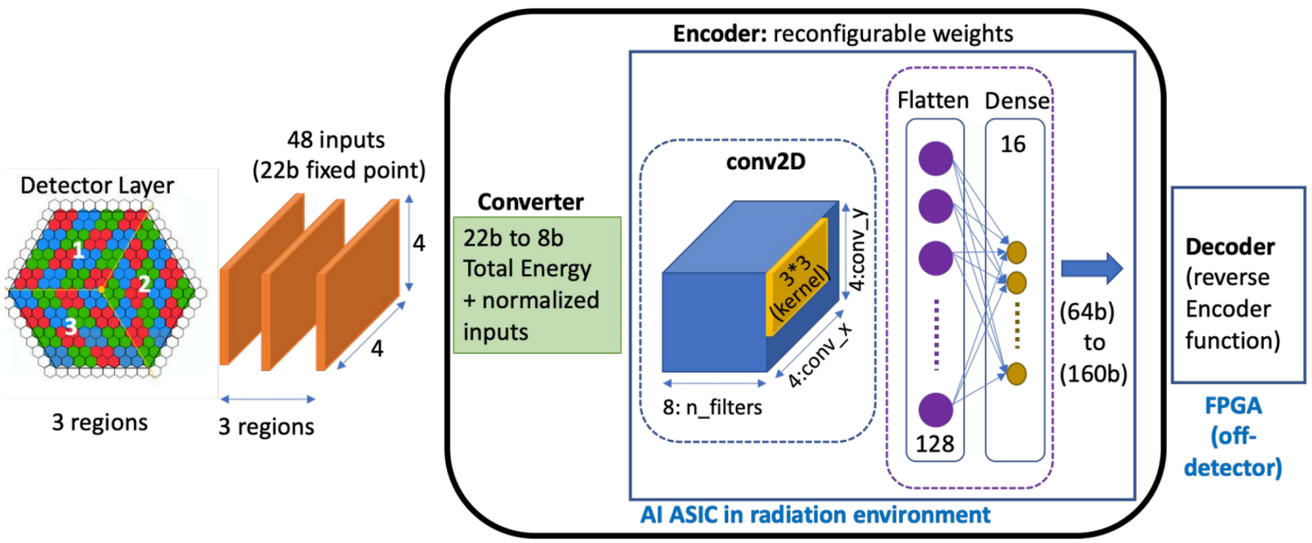
High Granularity Calorimeter

AutoEncoder Algorithm

- Development of a machine learning algorithm for data compression on the detector



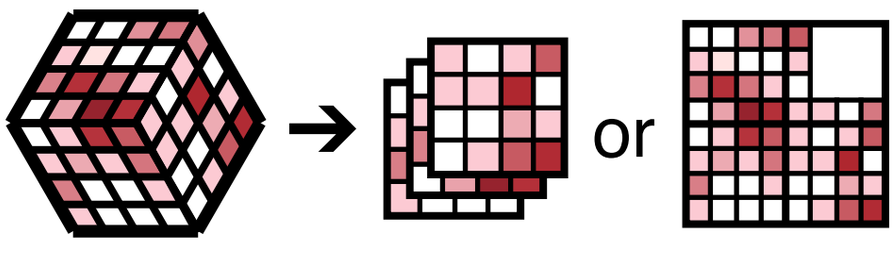
- "Image" of trigger cells taken as input to a Convolutional Neural Network (CNN), and compressed to latent space which can be transmitted to backend electronics
  - Encoding takes place on ASIC
  - Fully reconfigurable: Weights of the network are programmable, network can be retrained after installation
  - Algorithm can be customized to specific location on the detector, and the evolving conditions of the detector



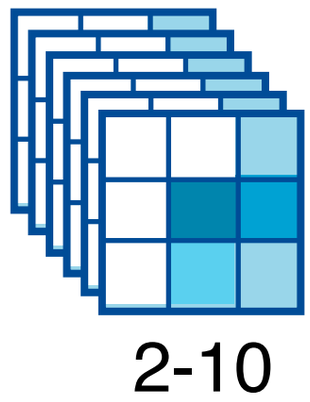
HGCAL

Autoencoder Algorithm Optimization

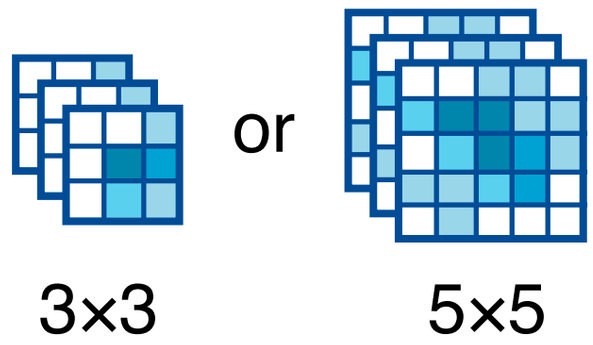
Geometry mapping



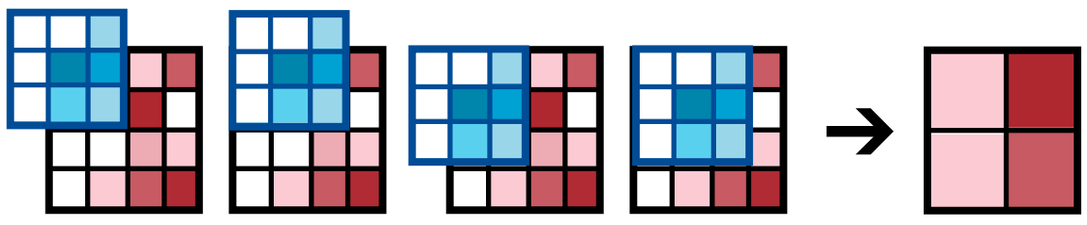
of conv2D filters



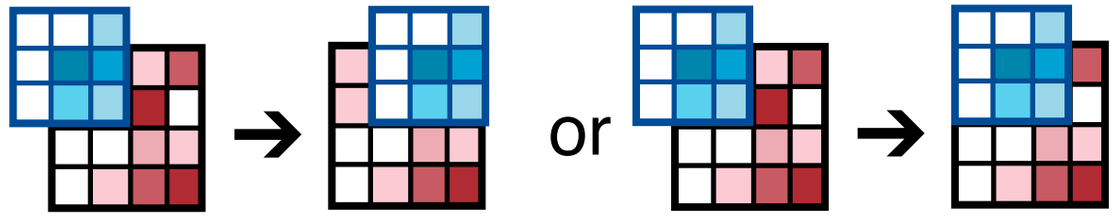
conv2D kernel size



Max pooling conv2D outputs

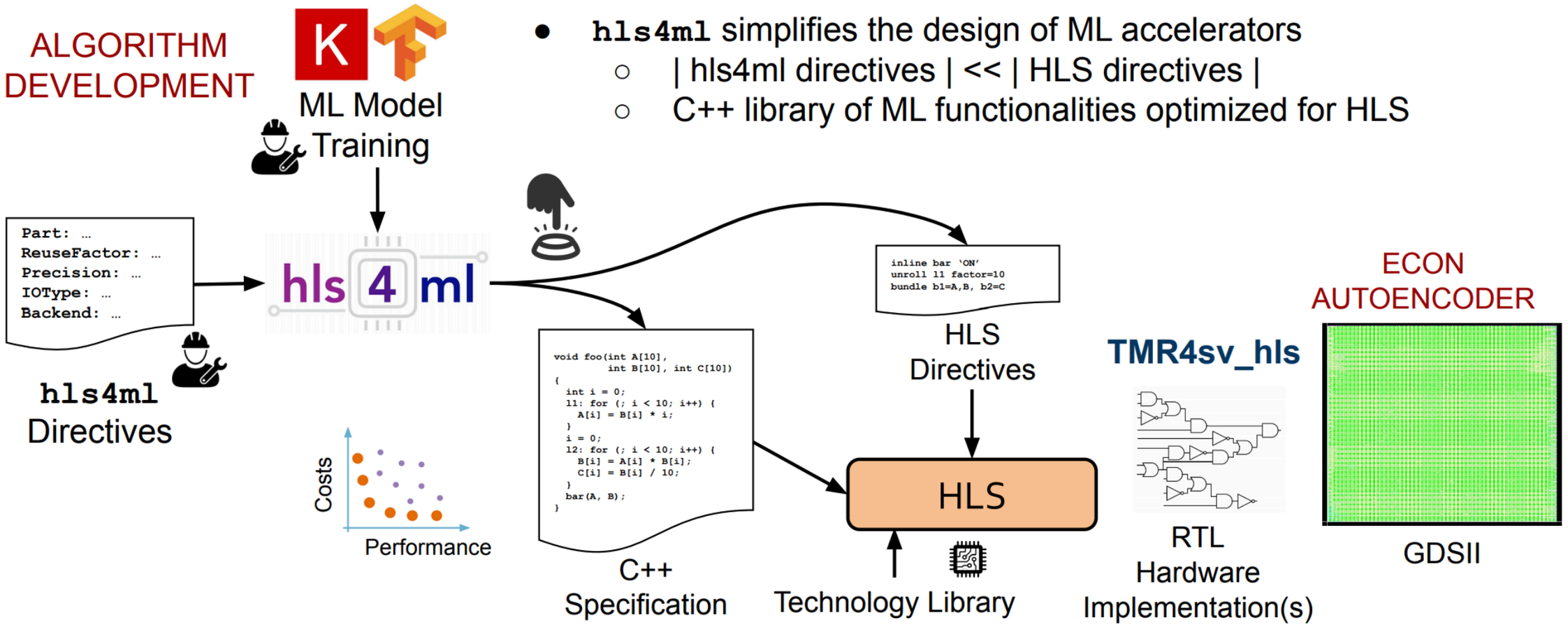


conv2D kernel stride

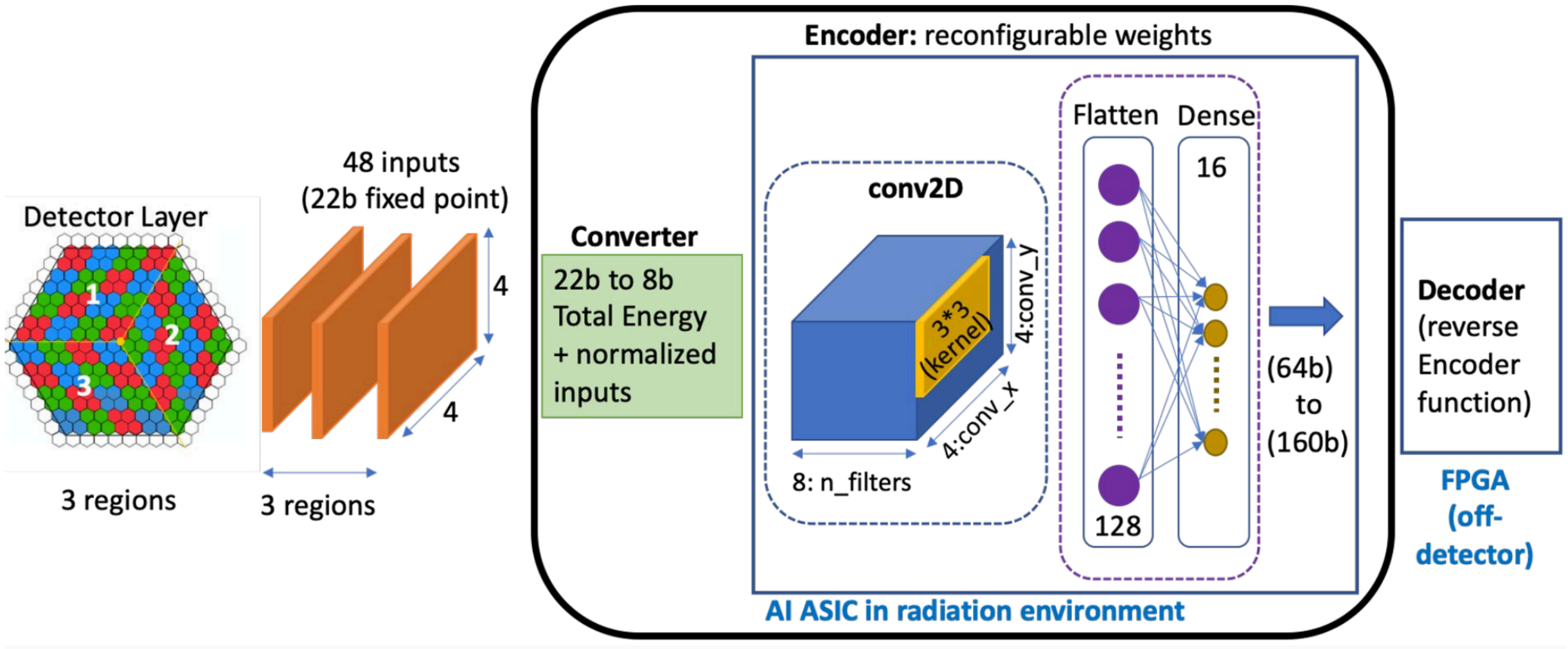


HGCAL

Autoencoder Development Workflow



- **`hls4ml`** simplifies the design of ML accelerators
  - | hls4ml directives | << | HLS directives |
  - C++ library of ML functionalities optimized for HLS


Detector Layer
1
2
3
3 regions
48 inputs
(22b fixed point)
4
4
3 regions
Encoder: reconfigurable weights
Converter
22b to 8b
Total Energy
+ normalized
inputs
conv2D
3*3
(kernel)
4:conv_y
4:conv_x
8: n_filters
Flatten
Dense
16
128
(64b)
to
(160b)
Decoder
(reverse
Encoder
function)
FPGA
(off-
detector)
AI ASIC in radiation environment

HGCAL

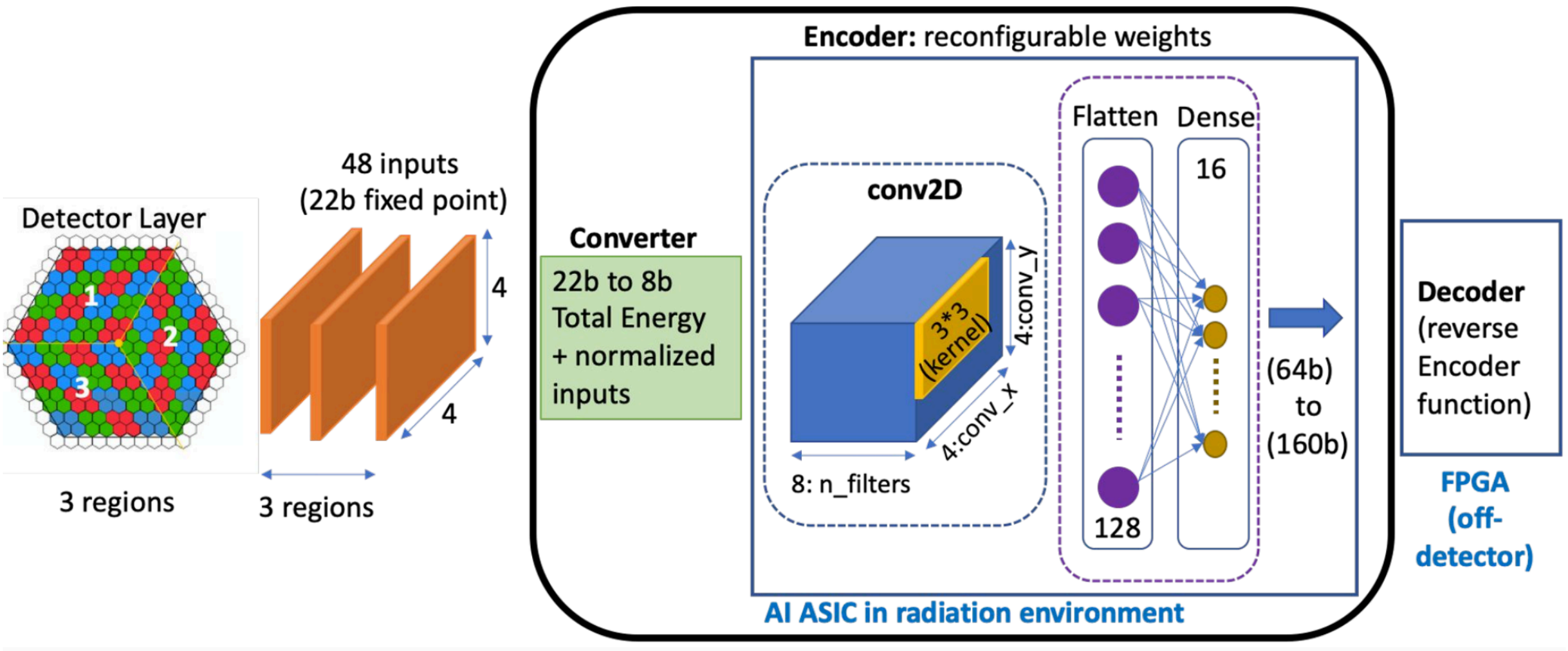
Autoencoder Algorithm Optimization

- Numerous choices of

	Network Architecture					Relative Power & Area		Relative Performance	
Test feature	**Geometry**	**# filter**	**kernel**	**stride**	**pooling**	**# params**	**# operations**	**EMD Mean**	**EMD RMS**
Reference	4x4x3	8	3x3	1	none	1.00	1.00	1.00	1.00
4x4x3 -> 8x8	**8x8**	8	3x3	1	none	2.73	1.76	0.64	0.41
max pooling	8x8	8	3x3	1	**2x2**	0.71	0.97	0.59	0.33
3x3 -> 5x5 kernel	8x8	8	**5x5**	1	2x2	0.99	2.76	0.64	0.35
pooling -> stride=2	8x8	8	3x3	**2**	**none**	**0.94**	**0.59**	**0.76**	**0.46**
8 -> 10 filters	8x8	**10**	3x3	2	none	1.17	0.73	0.73	0.43
8 -> 6 filters	8x8	**6**	3x3	2	none	0.70	0.44	0.85	0.57

HGCAL

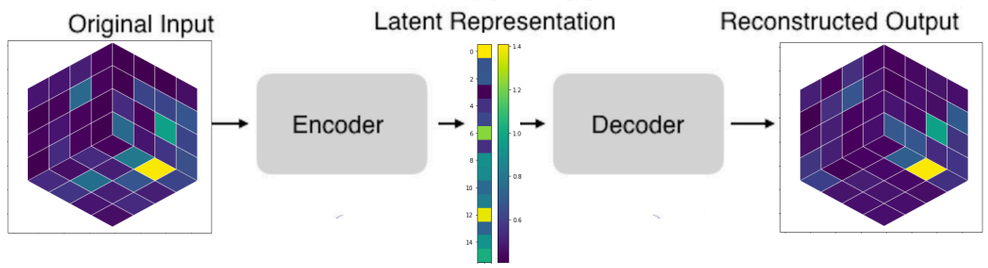
AutoEncoder Algorithm



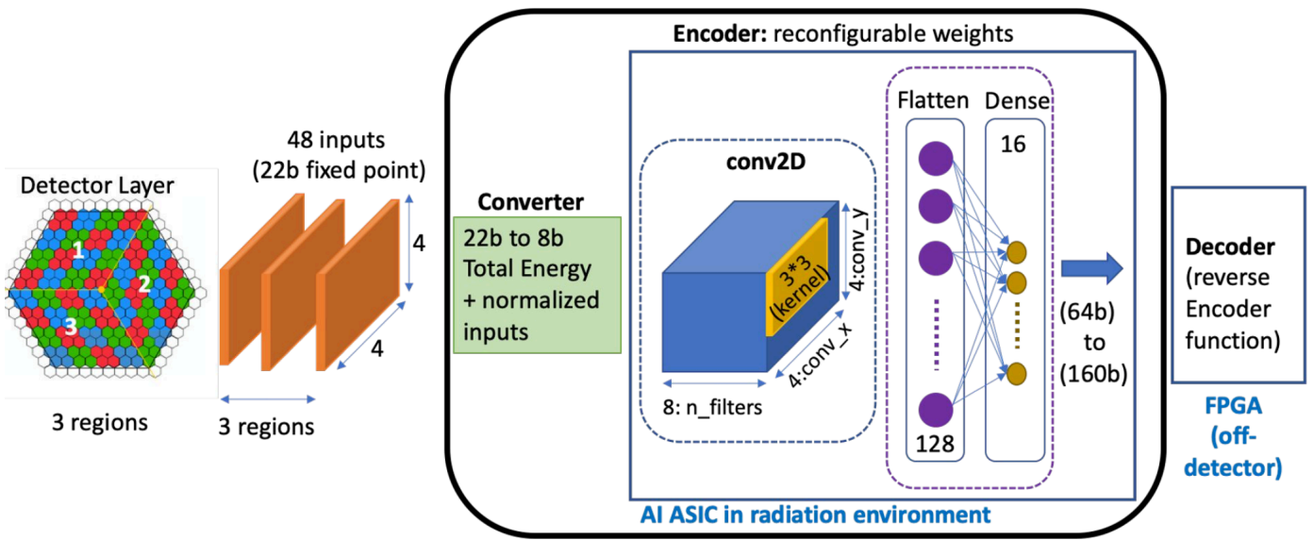
High Granularity Calorimeter

AutoEncoder Algorithm

- Development of a machine learning algorithm for data compression on the detector



- "Image" of trigger cells taken as input to a Convolutional Neural Network (CNN), and compressed to latent space which can be transmitted to backend electronics
  - Encoding takes place on ASIC
  - Fully reconfigurable: Weights of the network are programmable, network can be retrained after installation
  - Algorithm can be customized to specific location on the detector, and the evolving conditions of the detector



High Granularity Calorimeter

Design Verification

- Working closely with the engineers Fermilab ASIC Design group
- Developed software based emulation of full functionality of the ASIC
  - Provides bit-wise predictions of values throughout the chip
  - Essential for testing and verification of ASIC design
  - Independent implementation from ASIC designers, has been critical in discovering and correcting bugs in ASIC design
- In collaboration with ASIC engineers, developed coverage and testing plans to ensure full performance of the design